Sustainable Materials and Technologies in the Built Environment: Duke Athletics as a Case Study

by

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Executive Summary

In 2011, Duke University began a major fundraising campaign, with a significant portion of the money being allocated to several construction projects across campus, of which are either currently under construction or within the planning phases. Because of the university's strong commitment to sustainability, as outlined in Duke's Climate Action Plan, there's been significant interest in reducing the environmental impact of these projects. Unfortunately, the Facilities Management Department does not have the necessary resources to successfully analyze the materials and technologies going into these buildings, despite having the desire to do so.

Using the Chris and Ana Kennedy Tower – a press box to be shared between Koskinen Stadium and a new track & field facility – as a case study, this project compiles sustainability best practices for use by the Facilities Management Department in the development of this project and those that will follow in regards to the most prevalent materials and technologies. This was achieved through a literature review and life cycle assessment to best understand the environmental impacts associated with each. As a result, individual recommendations were made for each of these, along with overall recommendations that call for great upstream transparency from suppliers and the opportunity for further studies to be done expand the framework that has been established by this study.

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I. Introduction

In February 2011, Duke University officials announced that they would begin efforts to raise $100 million for a number of construction projects on behalf of Duke Athletics as a part of the Duke/Forward fundraising campaign (Featherston, 2012). One of these planned construction projects is a remodel of Wallace Wade Stadium, which includes the removal of the stadium's running track. As a result, one of the first stages of the campaign will be building a new track stadium, to be constructed adjacent to Koskinen Stadium, the current home of Duke's soccer and lacrosse teams. The project will include a state-of-the-art track and brick grandstands, along with a new press box, the Chris and Ana Kennedy Tower. Kennedy Tower will be located between Koskinen and the track stadium to serve both facilities (Featherston, 2012).

The previously mentioned Duke/Forward campaign reaches well beyond the athletic department, with a large portion of the funding going towards the growing number of construction projects, either in progress or in planning phases in all areas of the university. In light of Duke's strong commitment to sustainability, which includes a Climate Action Plan that targets for the campus to be carbon neutral by 2024, this construction must be scrutinized through an environmental lens in order for it to best reflect the university's values. Having said that, Duke Facilities Management Department (FMD) is seeking to obtain more effective tools to assist them in procuring sustainable technologies and materials.

The purpose of this project is to begin the process of creating such a framework, in the form of a guidebook that uses Kennedy Tower as a case study. By examining both the major materials used in construction and the technologies that might be implemented throughout building, the goal is provide Duke FMD with recommendations applicable for not just Kennedy Tower, but also future construction projects on campus.

Similar guides that are currently available, such as materials from the United States Green Building Council (USGBC) and BREEAM (Building Research Establishment Environmental Assessment Methodology), are often targeted to individuals that have pre-existing knowledge of sustainability issue (Pearson, 2010). Instead of taking that approach, the goal of this study is to appeal to the architects, engineers, and other construction-related personnel of Duke FMD who may not have this pre-existing knowledge. This is achieved through an overview of each material or technology, its associated environmental impacts and benefits, and examples of specific products that can be used on the project. While these products represent the current market at the time of study, it should be noted that these are only examples and that the materials available can change quickly – the goal of this framework is to provide Duke FMD with the knowledge necessary to make specific decisions on products, as opposed to making any explicit recommendations.

II. Materials and Methods

There are a significant number of different materials and technologies that go into a building like Kennedy Tower. Because of the scope of this project, not all of them can be included within the study. By selecting the most prevalent materials and technologies, the results will provide a robust overview of the most sustainable approaches for each.

For each material and technology that is included, an overview is given to offer greater context on its usage and manufacturing. In addition to that, any building code requirements and sustainability-related industry response are mentioned. More importantly though, the environmental impacts are further detailed, using life cycle assessment (LCA) data, which are then used to create recommendations relevant to Kennedy Tower.

To obtain life cycle assessment data, a number of sources have been used. For the materials provided on the bill of material estimates, Athena Impact Estimator for Buildings has been used. As the name suggests, this software is building-specific and is capable of doing whole-building analysis. For other materials, publicly-available LCA studies have been used, with individual studies attributed in the Works Cited section.

III. Material and Technology Overview

Ten different materials and technologies have been selected for this particular study. Four were chosen based on bill of material estimates provided by the general contractor working on the Kennedy Tower; these are the ones in Table 1 that have numerical figures pertaining to approximate usage in the project. The remaining six were chosen based on relevance and opportunity, in terms of reducing the building's overall environmental impact through their use.

Material or Technology	Quantity used (if available/applicable)
ABC/Stone	1,587 short tons
Sand	72 short tons
Cement	2,128 cubic yards
Rebar	12 short tons
Gypsum Board	-
Insulation	-
Paint	-
Green Roofing	-
Energy	-
Lighting	-

Table 1, Technologies and materials examined in this study

IV. Cement

Cement is not only one of the most widely used building materials, but also one of the most commonly available manufactured products in the world – approximately 1 ton of cement is produced every year for each human being on the planet (Huntzinger & Eatmon, 2008). This cement is then combined with an aggregate, along with water to produce concrete, which is a major part of Kennedy Tower's construction. Cement itself is a fine powder made up of clinker, gypsum and other additives; clinker is composed of a of calcium oxide, silicon dioxide, aluminum oxide, and iron oxide, which then is crushed and homogenized into a mixture. This "raw meal" is heated in a kiln to temperatures of up to 2000^0 C, forming a new compound made up of silicates, aluminates and ferrites of calcium. The clinker is then combined with gypsum and potentially other additives, such as blastfurnace slag, coal fly ash, natural pozzolanas, or limestone, and then ground to homogenization and bagged for shipping (Cement manufacturing process, n.d.).

The most common type of cement is Portland and can be categorized in two manners; the European standard EN 197-1 separates the material into five categories based on the percentage of clinker and the type of additives used. In the United States, the standard ASTM C180 also divides into another five categories: Type I (normal) for general purpose; Type II (modified) for resistance to alkali attack; Type III (high early strength) for withstanding high heat; Type IV (low heat) used for massive structures; and Type V (sulfate-resistant) for maximum alkali resistance (Cochez & Nijs, 2010).

	Types of cement	**% Clinker**	**Other Constituents**
CEM I	Portland	95-100	
CEM II	Portland-slag	65-94	Blastfurnace slag
	Portland-silica fume	65-94	Silica fume
	Portland-pozzolana	65-94	Pozzolana
	Portland-fly ash	65-94	Fly ash
	Portland-burnt shale	65-94	Burnt shale
	Portland-limestone	65-94	Limestone
	Portland-composite	65-94	Additives mix
CEM III	Blast furnace	5-64	Additives mix
CEM IV	Pozzolanic	45-89	Additives mix
CEM V	Composite	20-64	Additives mix

Table 2, Categorization of Portland cement under EN 197-1 (Cochez & Nijs, 2010)

What requirements are there for cement?
The 2012 North Carolina Building Code references a number of standards set by the American Concrete Institute's ACI 318. These include guidelines for the water-cementitious materials ratio and exposure categories and classes. While these are important, they do not apply directly to this study but should be more carefully considered when concrete has been mixed (Chapter 19: Concrete, 2012).

Environmental Impacts
Cement manufacturing, especially during the creation of clinker, is a highly destructive process in terms of carbon dioxide emissions. In fact, approximately 5% of all global carbon emissions originate from the manufacturing of cement, which speaks to the importance of moving towards making this process more sustainable (Huntzinger & Eatmon, 2008).

While the number of cement products has grown, Portland cement remains the most dominant on the market. Because of this, this study only surveys Portland cement and the available alternative processes that can be used in a similar application. To do so, a cradle-to-gate life cycle assessment by Huntzinger & Eatmon was used to examine the traditional version of a material against three alternatives – a blended version that contains pozzolans and/or fly ash; Portland cement with a portion of the cement kiln dust (CKD) emissions captured back using sequestration in waste materials; and Portland cement when CKD is recycled back into the kiln. Using a functional unit of 1 ton of cement, the study confirmed that the clinker process had the greatest impact in manufacturing cement (Huntzinger & Eatmon, 2008). Figure 1 below shows this information, along with the other allocations of environmental impact for each step of the traditional Portland cement manufacturing process.

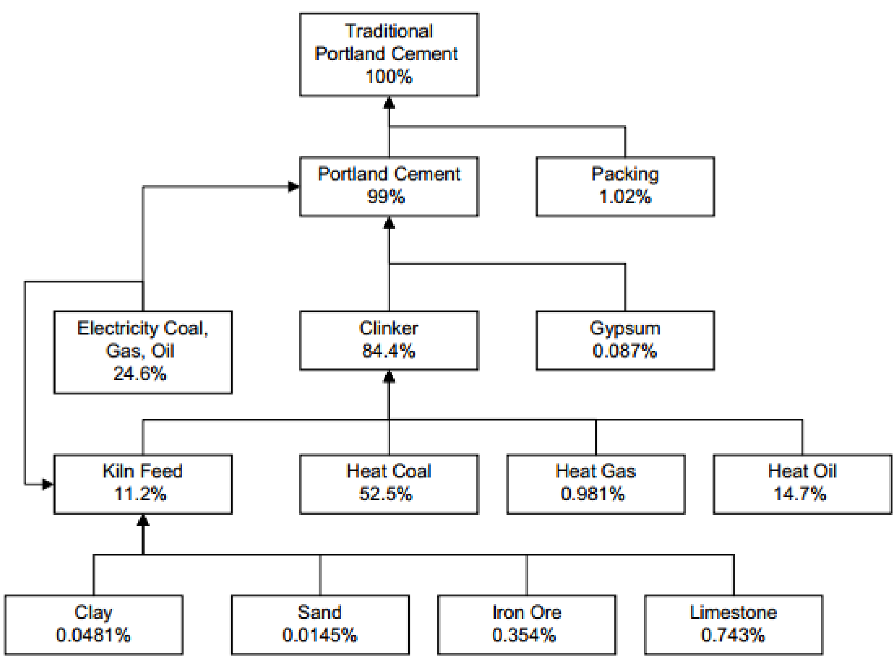

Figure 1, Life cycle network showing the allocation of environmental impact for each step of the traditional Portland cement manufacturing process (Huntzinger & Eatmon, 2008)

In terms of the three alternatives, there seemed to be little difference between tradition Portland cement and the substitute where CO_2 is sequestered, as well as the cement containing recycled CKD. On the other hand, the blended versions see a slight decrease in all impact categories when compared to the others. Table 3 shows the materials' weighted and combined impact scores, where the traditional material's impact score equals 2.0.

Environmental Impact Category	**Traditional**	**Blended**	**Recycled CKD**	**CO2 sequestration**
Greenhouse gas emissions	0.088	0.069	0.088	0.084
Acidification	0.043	0.034	0.043	0.043
Eutrophication	0.006	0.005	0.006	0.006
Heavy metals	0.204	0.161	0.204	0.204
Carcinogens	0.003	0.003	0.002	0.003
Winter smog	0.039	0.031	0.039	0.039
Summer smog	0.009	0.007	0.009	0.009
Energy resources	0.05	0.04	0.05	0.05

Table 3, Classification of process inuts and outputs for Portland cement manufacturing into environmental impact categories (Huntzinger & Eatmon, 2008)

Recommendations

Based on the LCA results, cement blended with additives such as fly ash or pozzolans should be used whenever possible. In addition to that, contractors should avoid excessive cement in concrete design – studies have shown that a lower water-binder ratio is more effective in creating durable concrete when compared to high cemntitious content. Similarly, alternative binders with lower environmental impacts, such as lime and gypsum, can be used as a substitute for cement in some cases (Yeung, n.d.).

V. Rebar

Rebar (or reinforcement bar) is typically made from steel and is used to reinforce concrete and masonry structures (Rebar, n.d.). Concrete is strong in compression, but does not perform particularly well with tension, so rebar is cast to carry concrete's tensile loads. In many cases, rebar has heavy ridges on it to increase concrete's ability to bind with the steel. In addition to that, there are three ways in which rebar is differentiated – size, grade, and finish. In terms of size, rebar is typically classified by numbers which indicate increasing thickness; of the widely-available sizes, #3 is the thinnest (approx. 9.525 mm diameter), while #18 is the thickest (approx. 57.33 mm diameter). Another factor is the grade, which indicates tensile strength and stress resistance; there are a variety of grades available, with each chosen based on a project's needs. The last consideration is the finish – rebar is either black (without coating) or epoxy-coated (used in corrosive conditions) (Steel Rebar, n.d.).

What requirements are there for rebar?
The 2012 North Carolina Building Code specifies that all structural steel must follow AISC 360, which is released by the American Institute of Steel Construction (Chapter 22: Steel, 2012). This particular standard gives specifications for structural steel buildings; because the particular specifications are not known for Kennedy Tower, the design requirements have not been included in this study. In less specific terms, AISC 360 provides a framework for the tensile strength required from rebar, which is meant to prevent reinforced concrete from failing (Specifications for Structural Steel Buildings, 2010).

Environmental Impact
A large amount of rebar is manufactured from steel scrap, which is melted in large furnaces. In addition to steel, rebar also contains a number of alloying elements such as chromium, nickel, and manganese. Once combined, the alloy is rolled and finished and ready for use on a project (Environmental Product Declaration, 2013).

A life cycle assessment of rebar, based on the 12 short tons estimated to be used in Kennedy Tower, has been carried out, using Athena Impact Estimator for Buildings. Table 24 in the Appendix shows the impact categories for rebar; as the data shows, the greatest environmental impact of rebar comes from the manufacturing stage. On the other hand, there is no impact from the use phase. This means that the greatest potential for making rebar more sustainable would come from making changes in the manufacturing phase.

In an LCA done in 2006, the effect of recycled content in steel on greenhouse gas emissions was examined; while it pertains specifically to steel beams, rather than rebar, it can still be used for illustrative purposes. As Table 4 shows, decreasing the recycled content in steel subsequently increases CO_2 emissions. Because the steel manufacturing process is so incredibly energy intensive, utilizing scrap materials significantly reduces the life cycle impacts; in fact, the energy required to produce stainless steel from scrap is less than a third of the energy used to produce stainless steel from virgin sources (Johnson, Reck, Wang, and Graedel, 2007).

Recycled Content	CO_2 emissions (kg/SF)	% change
95%	1.242	-
75%	1.273	+2.5%
50%	1.311	+3.0%

Table 4, Carbon Dioxide Emission per Steel Content in Beam Production (Johnson, 2006)

Industry Response

Unfortunately, rebar manufacturers have done very little to increase the sustainability of their products. This may be a result of the lack of consideration of rebar in the LEED Rating System – the only credit that it could potentially qualify for is recycled content. So in essence, the recycled content of rebar is where the industry's sustainability measures begin and end.

Recommendations

Because there is no material disclosure from manufacturers, it becomes difficult to make specific recommendations for rebar. Still, the highest feasible amount of recycled content should be pursued, along with having the rebar manufacturing facility located as close to the project site as possible. In addition to that, black rebar should be utilized if the project allows – while an LCA has not been done on the subject, epoxy coating introduces additional environmental impacts that could be potentially avoided otherwise.

VI. Sand & Stone

Sand (or fine aggregate) is typically used in construction projections as an ingredient in concrete. Stone, as well as sand, can be used as general fill and road construction and stabilization. While these are naturally occurring materials, resources and financial constraints in certain geographies also allow for their production through the crushing bedrock (Bolen, 2011). In addition to these primary aggregates, there is a market for recycled materials, coming from sources such as concrete and asphalt. Because of the nature of these recycled aggregates, their use is more restricted than primary aggregates like sand. In the case of recycled asphalt, two-thirds of the material is used as aggregates for road base, while the other third is reused as aggregates for new asphalt hot mixes. Similarly, the majority of recycled concrete is used as road base, with the remainder used for new concrete mixes, asphalt hot mixes, high-value riprap, and products like general fill (Goonan, 2000). In the case of both asphalt and concrete, the road base is the dominant use of recycled materials, due mainly to quality issues. According to the USGS, the use of recycled materials like these has been increasing, but still remains a small percentage of aggregates consumption (Bolen, 2014).

What requirements are there for sand and stone?
The 2012 North Carolina Building Code contains standards regarding the load-bearing value of soils, which includes sand (Chapter 18: Soils and Foundations, 2012). While the exact amount of sand that will be used in Kennedy Tower is currently unknown, recycled materials may have to be carefully studied for their load bearing characteristics if considered for use in the building.

Environmental Impacts
The environmental impact of an aggregate varies greatly due to differences in manufacturing processes across the different materials. Figure 2 shows these processes across four types of aggregates; hard rock, land-won sand and gravel, marine, and recycled.

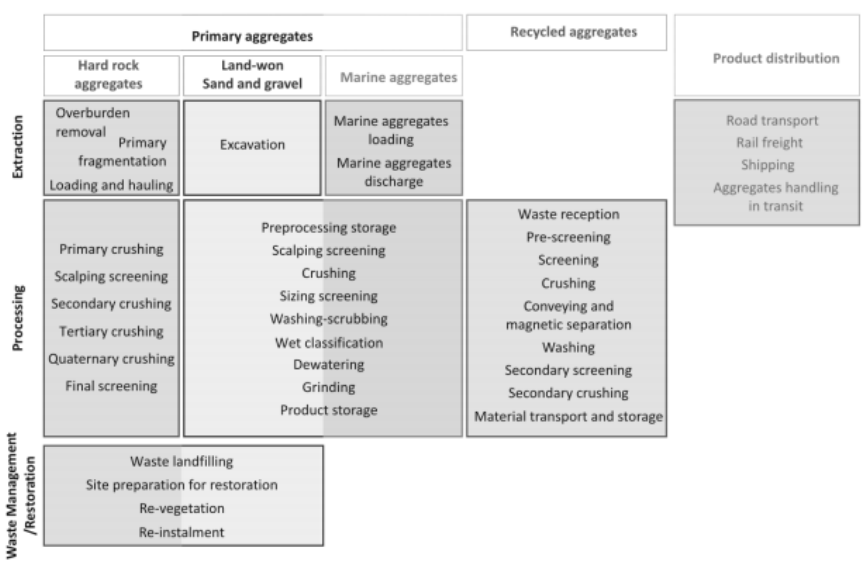

Figure 2, Manufacturing processes across aggregate categories (Korre & Durucan, 2009)

Figure 2 is part of a cradle-to-gate life cycle assessment of the previously mentioned aggregates done by researchers at Imperial College London. In this study, the functional unit is one metric ton of aggregate, with a comparison done between crushed rock, land won sand and gravel, marine sand and gravel, and recycled aggregate. The life cycle inventory assessment for each of these is found in the Appendix, while a total impact comparison is found in Table 5, below.

	Crushed rock	**Land won sand and gravel**	**Marine sand and gravel**	**Recycled aggregate**
Global Warming (kg CO2 eq.)	1.48 - 2.52	0.27 - 2.39	34.10 - 41.61	2.42
Eutrophication (kg PO4 eq.)	5.51E-04 - 8.78E-04	1.66E-04 - 7.43E-04	9.32E-02 - 0.115	7.06E-04
Acidification (kg SO2 eq.)	8.58E-03 - 1.48E-02	1.34E-03 - 1.35E-02	0.606 - 0.747	1.21E-02
Photo-oxidant formation (kg ethylene eq.)	6.78E-04 - 9.94E-04	1.61E-04 - 8.47E-03	4.83E-02 - 5.95E-02	8.00E-04
Human toxicity (kg 1,4-DB eq.)	3.37E-01 - 4.08E-01	1.25E-01 - 3.49E-01	8.83 - 10.89	1.73E-01
Freshwater Aquatic Ecotoxicity (kg 1,4-DB eq.)	5.98E-03 - 9.00E-03	1.58E-03 - 6.50E-03	4.09 - 5.06	1.96E-03
Marine Aquatic Ecotoxicity (kg 1,4-DB eq.)	124.74 - 198.40	27.4 - 152.92	315.60 - 334.60	3.05E+01
Terrestrial Ecotoxicity (kg 1,4-DB eq.)	2.71E-03 - 4.10E-03	6.99E-04 - 2.98E-03	2.34E-02 - 2.68E-02	8.62E-04
Ozone layer depletion (kg R11 eq.)	1.85E-07 - 3.39E-07	2.65E-09 - 4.44E-07	3.30E-09 - 1.75E-07	2.83E-07

Table 5, Total life cycle inventory impacts across aggregate categories (Korre & Durucan, 2009)

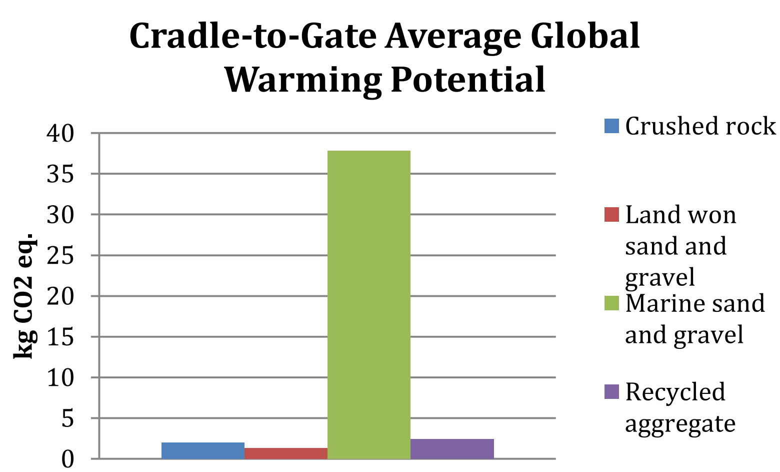

Figure 3, (Korre & Durucan, 2009)

With the exception of ozone layer depletion, marine sand and gravel has the greatest environmental impact across all categories. For the three remaining aggregate types, the results are much closer, often to the point where it becomes difficult to decipher any difference

Industry Response

For the purposes of LEED certification, recycled aggregates can often be used in the place of sand and will count towards the “Building life-cycle impact reduction” credit under the new v4 (Building Life-Cycle Impact Reduction, 2014). Beyond that, there has been no industry-wide movement towards reducing the environmental impact of sand or other aggregates.

Recommendations

In the case of sand, stone, and other aggregates, any materials sourced via marine routes should be avoided entirely, due to their comparatively large life cycle impact. With Duke concerned largely with the quantity of their carbon emissions, land won sand and gravel seem to be the best choice in that area, provided that the material is sourced locally. In that case that recycled aggregates are used, their quality needs to be assessed due to potential performance issues.

VII. Gypsum board

Gypsum board is the most commonly used construction material for interior wall surfaces; it's also commonly known as drywall, Sheetrock® (the proprietary name for the products sold by the United States Gypsum Corporation), plasterboard, or wallboard. While some gypsum board is manufactured from the naturally occurring sulfate mineral of the same name, an increasing amount of panels are made either partially or fully with synthetic gypsum, which has become easily obtainable as a byproduct of a number of industrial activities (Gypsum, n.d.). The most prevalent of these comes from the flue-gas desulfurization (FGD) process that occurs at coal-generating power plants, generating the substance that is more commonly known as fly ash. As of 2010, approximately 45% of all gypsum used by U.S. manufacturers of gypsum board in 2010 was synthetic, continuing an upward trend that's seen a 900% increase in synthetic utilization, as compared to 15 years ago. In addition to the gypsum, the boards also include paper facing on both sides; as a testament to the LEED rating system's influence on the on the construction, virtually all of this is recycled, coming from newsprint and consumer waste materials (Gypsum Recycling, n.d.).

What requirements are there for gypsum board?
There are a number of options available to consumers when it comes to gypsum board. These include standard gypsum board, mold board (mold-resistant gypsum board), greenboard (moisture-resistant gypsum board), and Type X (fire-resistant gypsum board), although there are options that include more than one of these characteristics (Choosing Drywall, 2013). Per the 2012 North Carolina Building Code, all gypsum wallboard must conform to the ASTM C 36/1396 standard, which calls for Type X gypsum board that meets specific fire safety requirements (Important Fire Safety Information, 2011). Similarly, due to Duke's location in the southeast, both moisture and mold issues must be taken into consideration. Lastly, attention must be paid to the presence of volatile organic compounds (VOCs) – these are chemical compounds that can off gas from gypsum board panels (amongst other products) and adversely affect the health of a building's occupants (An Introduction to Indoor Air Quality, n.d.).

Environmental Impacts
The current state of the American gypsum industry presents a major issue in terms of overall environmental impact – in purchasing gypsum products, consumers are not given a clear choice between those made with natural gypsum and those with synthetic gypsum. In fact, most gypsum board panels are composites of the two. While it seems sensible to think that utilizing synthetic gypsum over natural gypsum would be the more environmentally preferable option, both sides come with tradeoffs. The use of natural gypsum comes with the associated air and water emissions, along extensive habitat destruction, while synthetic gypsum is mostly commonly associated with coal-fired power generation.

In order to better understand the environmental harm brought about gypsum board, a "cradle-to-gate" life cycle assessment was undertaken by the Athena Sustainable

Materials Institute at the request of the Gypsum Association and its members. In terms of this particular study, cradle-to-gate refers to the scope of the assessment; it begins with the extraction of raw materials (the “cradle”) and ends at the manufacturing plant (the “gate”), after which the gypsum board is either shipped to a distribution center or directly to the product user. The use, maintenance, and end-of-life phases that follow have not been considered (Bushi & Meil, 2011).

Included	Excluded
• Input raw materials • Input process ancillary materials • Input energy supply • Operation of primary production and pollution abatement equipment • Operation of mobile support equipment • Input water (for process and cooling) • On-site recycling of post-consumer gypsum wallboard (GWB) waste • Packaging of products • In-bound transportation of raw materials, ancillary materials, intermediate products and fuels • Overhead (heating, lighting) of manufacturing facilities • Out-bound transportation and disposal of generated waste	• Fixed capital equipment • Hygiene-related water use • Transportation of employees

Table 6, Life Cycle Inventory System Boundary (Bushi & Meil, 2011)

Three major process systems within the cradle-to-gate boundary have been chosen because they best encapsulate the collection of unit processes – these are the gypsum quarry process, gypsum wallboard manufacturing, and gypsum paper manufacturing. The combination of latter two systems result in two functional units, which are primary focus of the study: ½” Regular gypsum wallboard and 5/8” Type X gypsum wallboard in the quantity that is capable of covering an area of 1000 square feet, in addition to 1,000 square feet of gypsum paper. Only the results for the 5/8” Type X gypsum wallboard has been considered in relation to Kennedy Tower, due to the previously mentioned building codes that apply to the project. For the quarry process system, the functional unit is the production of one short ton of natural gypsum ore. Also examined is synthetic FGD gypsum, which is a resulting co-product of the coal-fired power generation process (hence why it doesn’t have its own process system). While synthetic FGD gypsum has the same molecular composition as mined gypsum, it must undergo additional processing to be utilized in gypsum board manufacturing. These include dewatering and transportation to the relevant manufacturing facilities, both of which have been included within the system boundary for this assessment (Bushi & Meil, 2011).

The results of this study shows that the manufacturing of 1,000 square feet of 5/8” Type X gypsum wallboard is responsible for 5.45 GJ of primary energy use. For sake of comparison, the average site energy consumption per American in household in 2009 was 94.6 GJ (Residential Energy Consumption Survey, 2009). According to 2010 Census data, new single-family homes averaged 2,392 square feet; a typical 12” x 12” room requires around 600 square feet of gypsum board (United States Census Bureau, 2010; How much does it cost to install drywall in a single room?, n.d.). Based on that information, the average new single-family home in the US would need approximately 9,967 square feet of gypsum board – or the equivalent of 54.3 GJ of embodied energy. In other words, the embodied energy in total gypsum board found in a new home is equivalent to nearly 60% of the site energy consumption that will take place there in a year (assuming that Type X gypsum wallboard is used).

Similarly, the same quantity of 5/8” Type X gypsum wallboard contributes 315 kg of CO_2 equivalent emissions, 78% of which is resulting from on-site manufacturing energy. In fact, two of three major contributing sources to the life cycle impact assessment (LCIA) results are onsite energy flows (both natural gas and electricity). While gypsum manufacturers can improve the energy efficiency of their facilities and transition towards using more renewables, it’s difficult for those on the purchasing end to directly affect these factors. The third major contributing source to the LCIA results was the gypsum paper manufacturing, a process that can be more directly influenced through purchasing (Bushi & Meil, 2011).

In terms of the assessment’s findings on the difference in impact between natural and synthetic FGD gypsum, the former causes greater environmental harm based on all LCIA indicators other than abiotic resource depletion and smog potential. In fact, the net impact of the FGD gypsum creates an environmental benefit due to its avoidance of the landfill, with the vast majority of the reductions coming through the smog potential indicator. This might lead to misinterpretation, though; the difference between synthetic FGD and natural gypsum is minimal across the majority of the LCIA category results (ranging between a 1% and 8% improvement in favor of synthetic FGD) (Bushi & Meil, 2011). Still, this is an improvement, especially when 50% of all synthetic gypsum was left unused and landfilled, as of 2009 (Gypsum Recycling, n.d.).

Industry Response

In order to identify interior products and materials that have low chemical emissions, Underwriters Laboratories (UL) acquired GREENGUARD in 2011 (About GREENGUARD Certification, n.d.). The GREENGUARD Certification guarantees that products meet stringent emissions standards based on established chemical exposure criteria, while GREENGUARD Gold Certification take that further and considers safety factors to account for sensitive individuals (such as children and the elderly in environments such as schools and healthcare facilities) (The GREENGUARD Certification Program, n.d.). A number of gypsum board panels that are compliant with the 2012 North Carolina Building Code have received the GREENGUARD Gold Certification and are listed in Table 19 in the Appendix.

Recommendations
Based on the previously mentioned LCA results, the aspects of gypsum board that require the greatest attention when considering its sustainable procurement are the source of the gypsum that goes into the boards, the means in which the paper is manufactured, and the proximity to the construction site. In addition to those three factors, the products should be verified by a third-party to indicate that they do not off gas harmful VOCs. Knowing these things, an ideal gypsum board selection for Kennedy Tower would have received a GREENGUARD Gold Certification and be manufactured as close to Durham as possible with a high percentage of synthetic FGD gypsum and recycled paper products.

VIII. Insulation

Insulation is a physical barrier, available in a range of different materials, which has the primary purpose of slowing the transfer of heat from warmer areas to colder areas (Insulation, n.d.). Insulation materials vary greatly in terms sources and properties, which makes its proper selection in relationship to a particular project, in general, more complicated than other building materials. They fall into two general categories, fiber and cellular; there are three further sub-categories that describe the material source – mineral (or inorganic), oil-derived (or organic synthetic), and plant/animal derived (or organic natural) (Insulation for Sustainability, n.d.). Figure 4 shows this relationship and lists some of the more common types of insulation.

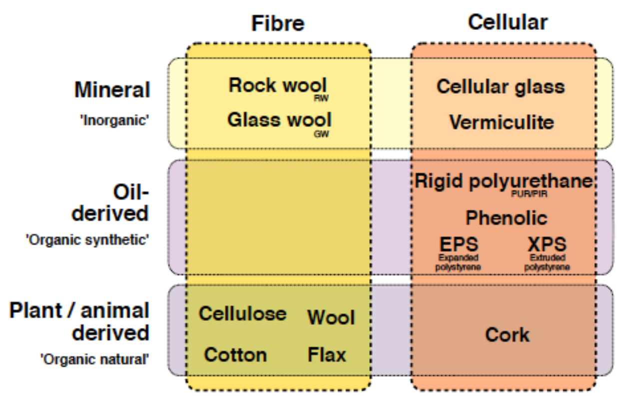

Figure 4, Classification of insulation materials (Insulation for Sustainability, n.d.).

With the wide selection of insulation type available on the market, it seems understandable that each has different applications – Table 21 in the Appendix details these uses.

What requirements are there for insulation?

An insulation material's ability to resist heat traveling through it is measured by its r-value, with a higher figure indicating a better thermal performance. In theory, a building that is outfitted with insulation that has the highest possible r-value (somewhere between R-30 and R-50, depending on the method by which it's measured) would be optimal, but in many parts of the country, this is neither necessary nor financially practical (Wilson, 2013). In an effort to create guidelines for insulation usage across the country, ASHRAE 90.1-2007 divides the US into different climate zones and suggests r-values for different structures based on location. In fact, the 2012 North Carolina Energy Code has adopted ASHRAE 90.1-2007 into law, meaning that all structures built in the state must insulate to the standards listed, which are found in Table 7. When the acronym 'ci' is used, this means continuous insulation; the code defines this as "insulation that is continuous across all structural members without thermal bridges other than fasteners and service openings."

The alternative to this is cavity insulation, which as the name suggests, only creates a thermal barrier over the wall cavity and allows heat transfer through framing studs. As shown in Table 7, cavity insulation requires a higher r-value because of the previously mentioned heat transfer.

Mass	R-9.5ci
Metal building	R-0 + R-15.8ci
Metal framed	R-13 + R-10ci
Wood framed and other	R-13 + R-7.5ci

Table 7, Climate Zone 4 Wall, Above Grade R-Values (Chapter 5: Commercial Energy Efficiency, 2012)

While there are no code requirements in to fire resistance, it’s another important factor to consider. All commercial insulation from reputable manufacturers should contain flame retardant, indicating that all insulating materials should be purchased from members of the North American Insulation Manufacturers Association (NAIMA).

Environmental Impact
Because of the variety of insulating materials available, their environmental impacts are widely different. Table 8 below shows a basic overview of the manufacturing process of common types of insulation, along with information about their potential to be recycled or reused.

Insulation Type	**Resource Consumption**	**Recycling/Reuse Potential**
	Batt/Blown	
Fiberglass, batt	Materials acquired through open pit mining; most include 30% recycled content	Recyclable, but no program currently exists; reuse possible but rare
Mineral fiber, batt	Made from molten slag, a waste product of steel production	Reuse possible but rare
Fiberglass, blown	Materials acquired through open pit mining; most include 30% recycled content	Recyclable, but no program currently exists; reuse possible but rare
Cellulose, blown	Most contain 75-85% post-consumer recycled content; up to 100% is possible	Recyclable, but no program currently exists; reuse possible but rare
	Rigid Board	
Expanded polystyrene (EPS)	Derived from non-renewable resources, crude oil and natural gas	Recyclable into packing foam, but not cost effective
Extruded polystyrene (XPS)	Derived from non-renewable resources, crude oil and natural gas	Recyclable; high reuse potential if not damaged
Polysiocyanurate	Derived from non-renewable resources; contains at least 9% recycled content (PET bottles)	Recyclable, but no program currently exists; reuse possible but rare
	Expanding Spray Foam	
Closed-cell spray polyurethane (SPF)	Can be made from recycled products like PET bottles	Not reusable or recyclable because of bonds with wall
Open-cell polyicynene	More resource efficient than closed-cell foams	Not reusable or recyclable because of bonds with wall

Table 8, Resource consumption and recycling/reuse potential by insulation type (Insulation, n.d.)

The insulation types in Table 8 only represent a portion of all materials available, which means that a comprehensive comparative life cycle assessment encompassing the entire market is not available. The most complete study, done by Melchert Duijve at Utrecht University, prioritized the materials based on four properties: price, thermal conductivity, resource availability, and practical application. Based on his analysis, he chose eight materials, in which he would analyze the impact of each insulating material need for the insulation of 1m^2 cavity wall surface to an r-value of R-19.9. It's important to note that this study was done from a Dutch perspective and doesn't completely carry over to the American insulation market, but still provides important insight, due to its comprehensiveness. Having said that, the eight materials studied are listed in Table 9, along with their input parameters.

Material	**Density (kg/m^3)**	**Thermal conductivity (W/m·K)**	**Mass of functional unit (kg)**
Glass wool	25 – 28	0.033 – 0.035	2.99 – 3.30
Rock wool	45 – 70	0.033 – 0.035	5.40 – 8.10
Gray EPS	15 – 16.6	0.032	1.65 – 1.83
White EPS	15 – 16.6	0.036 – 0.040	1.90 – 2.25
Flax	30 – 38	0.038 – 0.042	4.20 – 4.94
Hemp	38	0.040	5.32
PUR/PIR	30 – 33	0.024 – 0.028	2.46 – 3.05
PF-foam	35.6	0.021	2.71

Table 9, Density, thermal conductivity, and mass of functional unit of selected insulation materials (Duijve, 2012)

Expanded polystyrene (EPS) are split into a gray and white category for the study, because gray EPS contains graphite, which absorbs more radiation than white EPS, giving it a lower thermal conductivity (Duijve, 2012).

Figure 12 in the Appendix shows the results of the LCA; unfortunately, there doesn't seem to be one type of insulation that stands out as the best, in terms of environmental performance. Rock and glass wool consume the least energy, but are amongst the most damaging in the other categories. Gray and white EPS use slightly more energy, but offer superior performance in terms of acidification and eutrophication potential, along with ozone depletion (Duijve, 2012). Still, this study can only provide guidance based on particular impact categories.

Luckily, more product-specific information is available through UL's Environmental Product Declarations. These EPDs give information on the insulation's manufacturing location, material content, and an LCA detailing environmental impacts (Sustainable Product Guide, n.d.). Tables 22 and 23 in the Appendix show this information, giving a better clue on what particular products off the best environmental performance.

Industry Response
Environmental disclosures, such as the previously mentioned EPDs, are done on a voluntary basis. Similarly, UL has insulation as product category for GREENGUARD certification, ensuring that the materials are low VOC.

Recommendations
There are a number of insulation products that aren't made by mainstream manufacturers, including Ecovative, Bonded Logic, Green Fiber, NaturePro, and EcoCell, but many of these products have short track records in commercial buildings (if any at all). Because of this, their use isn't suggested. In terms of insulation from mainstream manufacturers, it remains difficult to gauge because of the differing needs in terms of performance and application in the building. Still, it's recommended that of these products, those with EPDs should be used, so the environmental impacts can be quantified. In particular, products that create the least possible harm across the impact categories should be preferred, along with other considerations such as price, manufacturing location, possession of third-party certifications, and compliance with applicable codes and law.

IX. Paint

In general, paints are classified as either solvent-based or water-based, with the major difference between the two being the increased presence of volatile organic compounds (VOCs) in solvent-based paint. By weight, the average solvent-based paint contain between 30 and 70% VOC, while water-based paints contain around 6% VOC. As a result of the greater presence of these VOCs in solvent-based paints, they've traditionally provided a glossier finish and have been better suited for use on wood and metal surfaces. On the other hand, water-based paints dry more quickly, lack the strong chemical smell that characterize its solvent-based counterpart, and have an easier clean up. Gradually, though, these differences have become less important as paint manufacturers have focused on improving building occupant health by reformulating water-based paints to have a similar performance to solvent-based, while keeping the VOC content low (Eco Priority Guide, n.d.).

But to only discuss paints in terms of solvent-based and water-based grossly simplifies the industry; in fact, it's one of the most complex in terms of building materials. One reason this is case is that most paints are designated for specific uses, such as wall paints or roof coatings (Sullivan, 2014). In addition to that, the number of subcategories that fall under either water- or solvent-based might make a project-specific even more difficult. These include more common types of paint, such as acrylic, alkyd, polyurethane, epoxide, and silicate, along with less common types like plant-based paints (Eco Priority Guide, n.d.). Table 25 in the Appendix gives a brief overview of these, along with arguments for and against their use.

What requirements are there for paint?
There is nothing that applies specifically to paint in the latest North Carolina Building code. While it doesn't apply to the Kennedy Tower project, a state law was passed in 2010 regarding the renovation and repair of buildings in which lead-based paint was used, and could potentially come into play in a future remodel at Duke (Lead-Based Paint Management, n.d.).

Environmental Impacts
A number of environmental impacts are introduced throughout the life cycle of paint. These fall under the categories of emissions, hazardous metals, durability, and curing and drying (Sullivan, 2014). In terms of emissions, the issue that is mostly commonly associated with paint is the presence of high levels of VOCs, which off gas from walls and have been linked to building occupant health issues. In fact, an EPA study showed that 9% of all VOC emissions from consumer and commercial products can be attributed to paint, demonstrating the seriousness of the matter (National Volatile Organic Compound Emission Standards for Architectural Coatings, 1998). As previously mentioned, VOCs are usually associated with solvent-based paints, but there are also particular factors within paints that determine the VOC content. One of these factors is color choice – many pigments used in colorants add VOCs to the base paint. In this case, this is tied more closely to shade and intensity, rather than the particular color; a

deeper hue requires higher amounts of colorant, which leads to higher levels of VOC emittance (Sullivan, 2014).

Concerns with emissions also extend beyond VOCs, extending to worries about the use of hazardous chemicals during surface cleaning, preparation, and renovation. The most prominent of these chemicals is methylene chloride (MeCl), which is found in paint strippers. Instead of affecting building occupants, these emissions affect construction crews, to the point where US EPA introduced regulation in 2011 that requires projects to notify the agency if they're using MeCl on a project and certify that they're using best management practices of the chemical (Sullivan, 2014).

In terms of hazardous metals, this is related mainly to the management of lead-based paint, which has been banned for decades. As previously mentioned, lead-based paint is only found in existing buildings and would not apply to Kennedy Tower.

The last two factors – durability, and curing and drying – correspond to the quality of the paint and by which its coatings were applied. In terms of durability, paint should remain vibrant and be easily cleanable, so additional coats don't need to be applied sooner than necessary. In the past, the most durable paints were also the most toxic, but recent advances have made headway in changing that. These include antifouling paints and zinc-based primers, which allow for reduced maintenance and greater longevity in certain scenarios. Curing and drying refers to the crosslinking of polymers into long chains, which gives paints the ability to form a film – the specification for this varies by the purpose of the paint. If done properly, the paint coat will lead to an improved durability and lifespan (Sullivan, 2014). As alluded to Table 25 in the Appendix, the more prominent types of curing methods are electron beam (EB) and ultraviolet (UV). Often curing is done through the presence of thermal oxidizers within the paint, which emit VOCs, but EB and UV systems instantly polymerizes coatings through radiant energy sources, eliminating the need for the oxidizers, and thus eliminating anywhere from the majority to all VOC emissions, depending on the formulation (UV Processing is Environmentally Friendly, n.d.).

From a more generalized perspective, life cycle assessment can show the difference between water- and solvent-based paints, in terms of environmental impact, even if the difference in VOC content is already well established. In a cradle-to-gate study done by The Athena Institute, the differences between a generic latex (acrylic) paint and generic oil-borne (alkyd) paint was examined. In this case, the functional unit was 1 kilogram of paint. Table 10 below shows the life cycle inventory data; by all accounts, the oil-based acrylic is more damaging to the environment (Norris, 1998).

Paint Type	**CO_2 (kg)**	**NO_x (kg)**	**Particulates (kg)**	**SO_2 (kg)**	**SO_x (kg)**	**Total Energy Input (MJ)**	**Water (m^3)**	**Solid Waste (kg)**	**Toxic Waste (kg)**
Acrylic	2.74	0.00902	0.00218	0.000602	0.0229	7.77	0.00691	0.254	0.168
Alkyd	3.67	0.0112	0.00257	0.00209	0.0362	11.4	0.0086	0.351	0.248

Table 10, Life Cycle Inventory Date of Acrylic and Alkyd Paints (Norris, 1998)

Industry Response

The paint industry has taken an aggressive stance towards increasing the environmental sustainability of its products, most of which has been surrounding the VOC content of paints. Examples of third-party programs that either certify or call for maximum VOC levels are USGBC's LEED rating system, the Master Painters Institute Green Performance Standard, GREENGUARD certification, Green Seal certification, and the South Coast Air Quality Management District (SCAQMD) rulings (Green Programs and VOC Regulations, n.d.). While all of these are broadly recognized and accepted within the industry, there seems to be consensus that SCAQMD's Rule 1113, which is where the VOC limits are found, is the gold standard. The purpose of the rule is to improve air quality in Orange County and the urban portions of Los Angeles, Riverside and San Bernardino counties in California by reducing VOC emissions, and has been transferred over to other programs, with LEED and Green Seal adopting them for their own use. According to industry experts, this is because of the strict and oft-updated updates of the standard, along with the comprehensive vetting efforts (Sullivan, 2013).

Recommendations

Choosing a low impact, high quality paint requires a highly pragmatic approach. While it's clear that the paint should follow SCAQMD's Rule 1113 to reduce VOC emissions, choosing between a water- or solvent-based paint is not as straightforward, despite the life cycle assessment results. According to a study done by Cal Poly State University's Albert C. Censullo on VOC emissions, the stated VOC content refers only to paint prior to application, when actual emissions occur during its application. He suggests a measure based on hiding power, which calculates the ability to cover a surface per volume of paint. Essentially, a project using a higher VOC paint could possibly use less paint because of its greater hiding power, as opposed to a low VOC paint with poor hiding power (Censullo, Jones, & Wills, 2005). Based on this information, it's recommended that a number of paints are tested prior to choosing the final product that will be applied to wall. Similarly, there is great potential in reducing environmental impact during the painting processes; this includes UV and EB curing processes and zinc primer coatings. While these don't apply to all surfaces, they are well worth considering.

X. Energy

When compared to other buildings on campus, Kennedy Tower will likely have a much smaller energy demand, due to its sporadic occupancy. This creates a situation where utilizing on-site renewable energy could potentially be feasible, especially if the building’s peak energy demand does not exceed the energy output of a renewable system. Because the roof of Kennedy Tower, requires a shade structure to cover what is planned to be a filming platform, use of a solar photovoltaic (PV) array could potentially integrate well into the building’s current plans. While there a number of different kinds of solar arrays, photovoltaic panels directly convert light into electrical energy for use within the building (Photovoltaic, n.d.). Switching towards a more renewable source of energy is particularly important at Duke, which purchases its energy from Duke Energy. Because of the university’s commitment to reducing its carbon emissions, it’s becoming increasingly important to move away from Duke Energy, of which 69.5% of the electricity it produced in 2012 came from fossil fuel sources (Environmental Performance Metrics, 2012).

Despite this fact, solar PV panels have not become a normal sight on campus (the Nicholas School of the Environment’s Environment Hall is the only building to have them), due to a handful of obstacles preventing this from being the case. The first of these obstacles is financial – electricity rates from Duke Energy are low by industry standards. At $0.0739 per kWh, it becomes difficult to justify the panels by any financial measure (Palumbo & Collins, 2013a). This extends to the fact that there are both federal and state tax credits available in purchasing the panels, of which the university is ineligible for because of its tax exempt status, thus making it unable to reap any price offsetting that the credits could provide. Similarly, panel owners can receive solar renewable energy credits (SRECs), which can then be sold into the market for profit – but the North Carolina market is “relatively non-existent” and has never developed into anything substantial (Where is the NC SREC Market?, 2010). Lastly, most PV systems need to be in close proximity to a utility substation (in this case, those owned by Duke Energy) to take advantage of any tax credits through the process of net metering. While this is not a technical issue – essentially, it’s necessary to provide proof to the utility that the energy that the system is receiving tax credits for is actually being generated – running the necessary infrastructure to a substation raises the capital costs and, subsequently, the levelized cost of energy (C. Collins, personal communication, April 3, 2014). As shown in Figure 5, Kennedy Tower is not located particularly close to any of the five substations found on campus (Palumbo & Collins, 2013b).

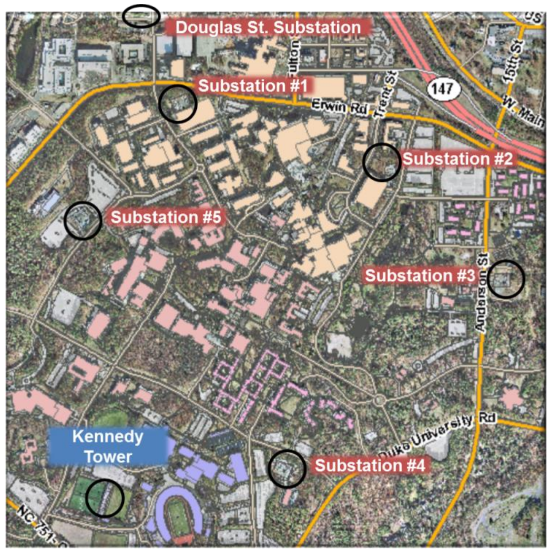

Figure 5, Location of substations at Duke University (Palumbo & Collins, 2013a)

Despite all of the factors going against it, the possibility for solar PV on Kennedy Tower remains. One potential financial solution is a sale leaseback scheme, in which Duke subleases the equipment. In typical sale leaseback transactions, a solar developer forms a limited liability company (LLC) that installs, operates, and maintains the solar array, incurring all expenses associated with those activities. The array is then sold by the developer to a tax credit investor (who is eligible for tax credits, as opposed to the university) and then would be leased back to the developer, who would use Duke's equipment sub-lease as collateral for its lease payment obligations to the investor. At the end of the lease term, there is typically an option to purchase the project from the investor (Groobey, Pierce, Faber, & Broome, 2010). Figure 6 shows this relationship in the context of the university.

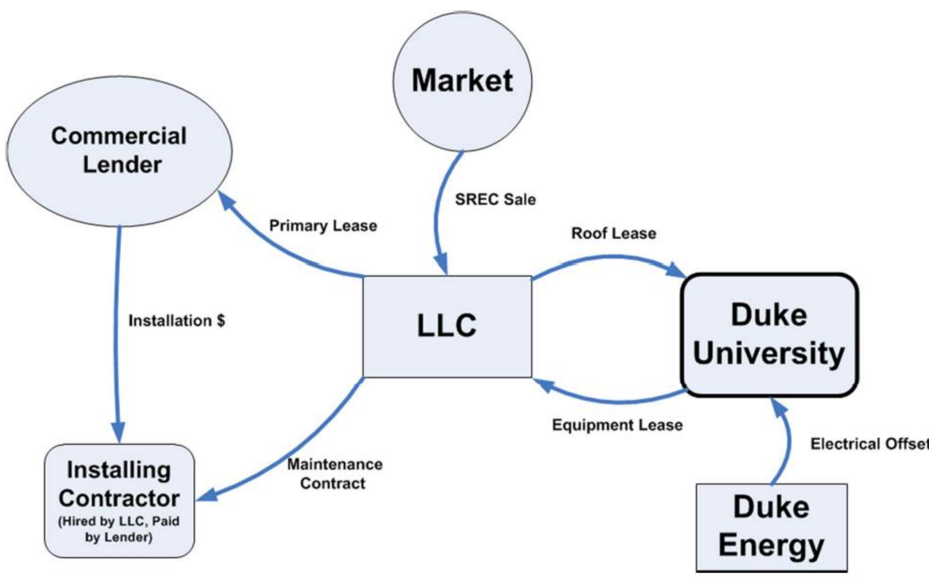

Figure 6, Overview of a potential sale leaseback scheme (Palumbo & Collins, 2013c)

This type of financing still does not ensure that cost of electricity from PV panels would be less than or even comparable to Duke Energy's current rate, and would require an in-depth study that falls outside of the scope of this project. The likelihood of success of a sale leaseback deal hinges on the university's willingness to pay more for renewable energy and likelihood that a rate structure change by Duke Energy could make the panels more competitive. In the case of a sales leaseback solar project on one of the university's parking garage that never came to fruition, Duke would have been losing significant amounts of money, but this is liable to change (Palumbo & Collins, 2013c). Even as electricity from the panels would avoid approximately 1.08 pounds of CO_2 on a kWh basis against Duke Energy's electricity, financial measures still need to be carefully considered against environmental impacts (Environmental Performance Metrics, 2012).

Another option for renewable energy at is the installation of micro wind turbines. While these do not produce a significant amount of energy -- six turbines installed on Arizona State University's Global Institute of Sustainability building produce enough electricity to power about 36 computers, or approximately between 2 and 9 kWh – they could serve as a visual representation of the university's commitment to sustainability (ASU Wind Turbines Generate Electricity and Interest, 2008; How much electricity do computers use?, 2012). This was the case at the Philadelphia Eagle's Lincoln Financial Field, where 14 micro turbines were installed as part of their greening efforts. According to Leonard Bonacci, the team's Vice President Of Event Operations & Services, joking claims that they puts out enough energy "to power a hair dryer", with their real importance coming from the dialogue that's started when fans see them (L. Bonacci, personal communication, November 23, 2013). Once again, the installation of such turbines hinges on the university's willingness to pay more for environmental reasons.

Figure 7, Lincoln Financial Field Wind Turbines (personal photograph, 2013)

XI. Green Roofs

While a significant portion of Kennedy Tower's roof is covered for filming, another portion is unused, leaving the possibility of introducing a green roof. There are a number of benefits that stem from green roofs, including increased energy efficiency, storm water filtration, and the reduction of the urban heat island effect, amongst many others. There are two basic types of green roof systems – extensive and intensive – which are generally differentiated by the depth of the growing medium. Both varieties typically consist of, beginning with the top, the plants, an engineering growing medium, a landscape or filter cloth, a drainage layer, and a waterproofing membrane. The differences are seen in that extensive green roofs have a growing depth of somewhere around 2 to 6 inches, while intensive systems can be between 8 inches and two feet (Peck & Kuhn, n.d.). Because of this, intensive green roofs tend to be accessible (along the lines of a garden), while extensive are not. Table 11, found below, further details the differences between the two, along with their respective advantages and disadvantages.

Extensive Green Roof	Intensive Green Roof
• Thin growing medium; little or no irrigation; stressful conditions for plants; low plant diversity.	• Deep soil; irrigation system; more favorable conditions for plants; high plant diversity; often accessible.
Advantages: • Lightweight; roof generally does not require reinforcement. • Suitable for large areas. • Suitable for roofs with 0 - 30° (slope). • Low maintenance and long life. • Often no need for irrigation and specialized drainage systems. • Less technical expertise needed. • Often suitable for retrofit projects. • Can leave vegetation to grow spontaneously. • Relatively inexpensive. • Looks more natural.	*Advantages:* • Greater diversity of plants and habitats. • Good insulation properties. • Can simulate a wildlife garden on the ground. • Can be made very attractive visually. • Often accessible, with more diverse utilization of the roof. i.e. for recreation, growing food, as open space. • More energy efficiency and storm water retention capability. • Longer membrane life.
Disadvantages: • Less energy efficiency and storm water retention benefits. • More limited choice of plants. • Usually no access for recreation or other uses. • Unattractive to some, especially in winter.	*Disadvantages:* • Greater weight loading on roof. • Need for irrigation and drainage systems requiring energy, water, materials. • Higher capital & maintenance costs. • More complex systems and expertise.

Table 11, Overview of differences between extensive and intensive green roofs (Peck & Kuhn, n.d.)

From a more general viewpoint, green roofs offer both public and private benefits over standard roofs. Likely the biggest attractions to implement a green roof system are the potential for energy savings and water retention. While actual savings are highly dependent on the building itself, studies have shown that they decrease both the need for air conditioning in the summer and heating in the winter. In fact, buildings like Kennedy Tower, that have a building envelope that is a large portion of the building and aren't exceptionally tall, can see cooling energy savings of up to 25%. In this case, an 8" thick green roof can have an insulative value of R-20, serving as the main reason such savings can occur (Peck & Kuhn, n.d.). Similarly, water retention is highly dependent on the building location. In a study done at University of Georgia, there is a significant difference in water retention between a traditional roof and a green roof, as shown in Figure 8. The study also includes non-vegetated green roofs (meaning that there was 10 cm of soil, but no plants present); with Athens, Georgia located in a fairly similar location as Durham, it seems that the application of this technology in the southeast is effective in retaining storm water (Prowell, 2003).

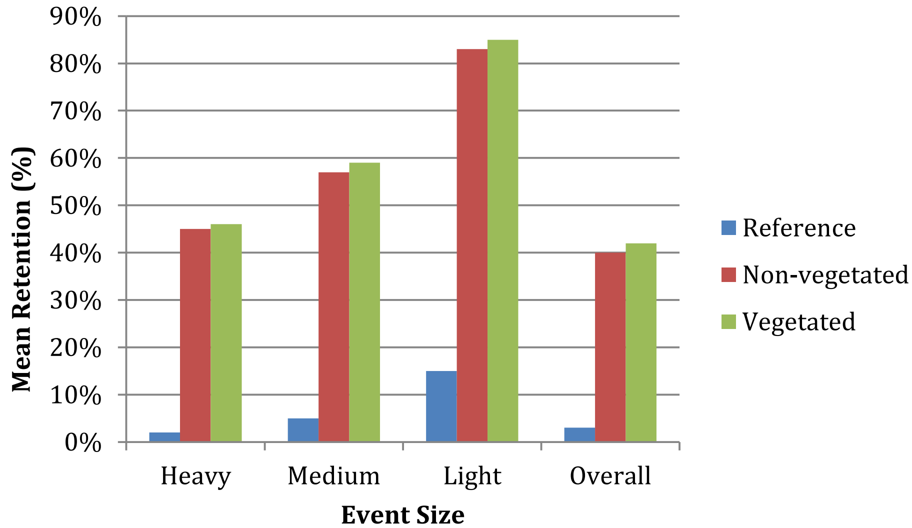

Figure 8, Mean storm water retention for different rainfall event sizes (Prowell, 2003)

In addition to energy savings from the insulative properties of green roofs, this can also serve as sound insulation, with specially designed systems reducing noise by up to 40 decibels. Similarly, the roofs provide the benefits of reducing the urban heat island effect, creating cleaner air, and creating habitat by connecting isolated habitat pockets (Peck & Kuhn, n.d.). Further benefits also include increased roof membrane protection and durability – studies show that green roofs can double the span of the traditional roof found beneath, reducing operational costs and the need for reroofing (Peck & Kuhn, n.d.).

While some of the previously discussed public benefits, might not be easily quantified for Kennedy Tower, literature exists that has explored this area of study. In an analysis done by Blackhurst, Hendrickson, & Matthews, the relative cost of materials and construction are compared energy savings, storm water retention, and the value of carbon sequestration, as shown in Table 12 on the next page. While direct energy savings aren't hugely significant, the value of indirect public should be strongly considered when looking at green roofs.

	Materials (%)	Construction (%)	Use phase Direct energy (%)	Heat island energy (%)	Storm water (%)	Sequestration (%)
Cost						
Single family	−31	−46	1.3	18	3.5	—
Multifamily	−36	−36	1.8	25	1.8	—
Commercial	−28	−44	3.0	24	1.4	—
All categories	−31	−44	1.7	20	2.9	—
GHG emissions						
Single family	−26	−4	4.5	64	0.51	0.53
Multifamily	−17	−3	5.1	74	0.19	0.23
Commercial	−17	−3	8.6	71	0.17	0.18
All categories	−23	−4	5.6	67	0.40	0.43
Energy use						
Single family	−0.08	0	6.5	93	0.73	—
Multifamily	−0.05	0	6.6	93	0.27	—
Commercial	−0.05	0	11.2	89	0.21	—
All categories	−0.07	0	7.7	92	0.55	—
Storm-water reductions						
Single family					84	
Multifamily					5	
Commercial					11	

Note: Negative values indicate a cost, emissions generated, or energy use.

Table 12, Relative costs and impacts by building type (Blackhurst, Hendrickson, & Matthews, 2010)

To better understand green roofs, it's important to examine the environmental impacts between extensive and intensive systems. While differences between traditional roofs and green roofs in general have been laid out previously, there are variances between the types of green roofs. This is best illustrated in a comparative life cycle assessment done at the University of Pittsburgh, which looked at three 12,000 square foot areas, each of which contained either an extensive green roof, an intensive green roof, or a conventional ballasted roof. The life cycle results were achieved using Simapro software on a cradle-to-grave basis. Data on energy consumption and storm water reduction was also collected; Table 13 below shows that both natural gas use and electricity use is lowest in the case of the intensive option.

Roof Option	**Annual natural gas use (therm)**	**Change in natural gas use**	**Annual electricity use (kWh)**	**Change in electricity use**
Control roof	9211	21	2,122,699	16,043
Extensive green roof option	9202	12	2,115,407	8,751
Intensive green roof option	9190	base case	2,106,656	base case

Table 13, Annual building energy consumption for the three roof alternatives (Kosareo & Ries, 2006)

Similarly, Table 14 shows the reduction in storm water run-off for each roof type, along with the ability of a roof system's to remove pollutants from the run-off (in this case, the mass of a pollutant is roof run-off per year is based on an average annual rainfall of 0.94 meters). As shown in Table 14, the intensive green roof performs best, with the greatest reduction in total run-off, along with the amount of pollutants found in the run-off.

Roof option	Control roof	Extensive green roof	Intensive green roof
Run-off reduction	33%	60%	85%
Lead (g)	15	9	3
Zinc (g)	25	15	6
Cadmium (g)	0.15	0.08	0.03
Copper (g)	100	60	20

Table 14, Storm water quantity and quality parameters for the three roof options (Kosareo & Ries, 2006)

In terms of the life cycle assessment results, the intensive green roof is once again the best performer of the three. Figure 9 shows the relative performance of the three roof alternatives across a number of impact categories. Kosareo and Ries's study shows that while intensive green roofs have the smallest environmental impact during their life cycle, this is generally not attributable to the materials that make up the roof, but the energy consumption avoided by the insulating properties of green roofs. Because of intensive green roofs have the thickest growing medium, energy consumption from within the building can be significantly reduced.

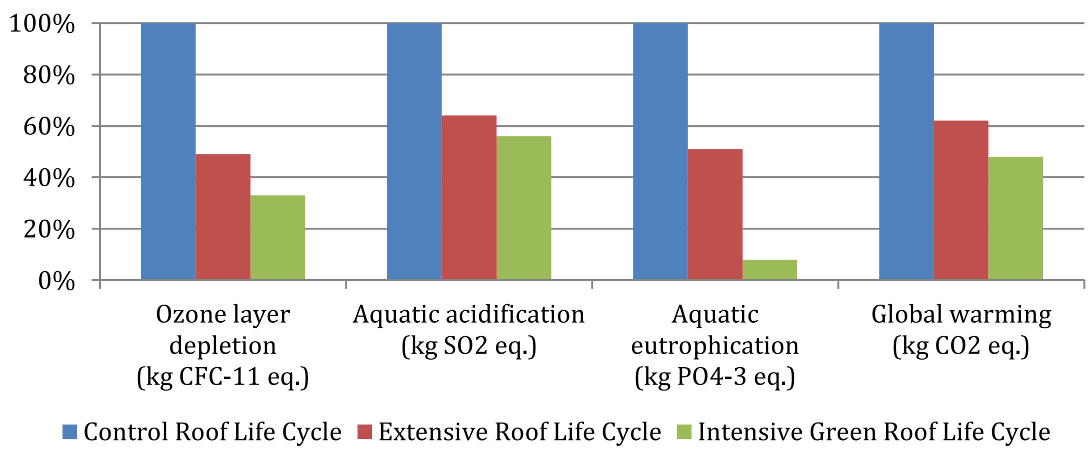

Figure 9, Relative performance of the three roof alternatives in terms of equivalence factors (Kosareo & Ries, 2006)

Not only are green roofs a visible representation of sustainability, but they also have real implications in terms of costs savings from energy consumption reductions. As the previous data has shown, intensive green roofs would seem to be the best route in terms of Kennedy Tower and other projects at Duke. In addition to these cost savings, there are the previously mentioned nonfinancial benefits, along with unique opportunities for students groups to potential "own" a green roof, amongst other things.

XII. Lighting

Because of the lack of detailed plans for Kennedy Tower, it’s not possible to undertake an extensive study of the building’s lighting for this project. Still, both Duke FMD and Duke Athletics have voiced their interest in exploring the possibility of using light-emitting diode (LED) fixtures for stadium lighting. Because the use of this technology in stadium and arena applications is still relatively new, it is often seen as cost prohibitive when compared to similar set ups that use high-intensity discharge (HID) system, such as metal halide lamps. According to the 2010 U.S. Lighting Market Characterization study done by the U.S. Department of Energy, high-intensity discharge systems accounted for 94% of all stadium lighting in the United States, while the remaining 6% could be attributed to halogen lamps (Ashe, Chwastyk, de Monasterio, Gupta, & Pegors, 2012). While that number has changed over the past few years, LED systems still are rare in this application. This can be attributed mainly to advances in LED technology – up until recently, LED fixtures could not properly illuminate a stadium with overheating. While still costly, these fixtures offer a number of advantages HID systems that don’t have to do with energy efficiency. These include lamp life – LEDs, according to manufacturer claims, can have up to a 100,000 hour life span, while metal halide fixtures require relamping after approximately 5,000 hours of usage. It must be noted that none of these products have been in use for 100,000 hours though, so this figure is based on projections done by manufacturers (M. Limpach, personal communication, October 30, 2013). Similarly, when the fixtures do fail, HID lamps burn out completely, while LED lights diminish in output over their operating life and relamping should occur when light output falls to approximately 70 percent of initial levels (Considerations When Comparing LED and Conventional Lighting, n.d.).

With these things in mind, I analyzed the potential effects of using LED stadium lighting around Kennedy Tower, as opposed to HID fixtures (in this case, metal halide). Because much of my information was based on architectural drawings, a number of assumptions had to be made to understand the difference in energy consumption and cost between the two. These assumptions included the lighting schedule, the system costs (which were extrapolated from a similar study done by Musco, a manufacturer that was recommended to me), and the actual number of lights needed. In regards to the project scope, I only considered the light fixtures that were associated with the track & field complex, along with those that illuminate Koskinen that were situated immediately next to Kennedy Tower – any fixtures outside of the immediate project footprint were not considered. Figure 14 in the Appendix shows an over of the workbook created in doing this analysis.

While the assumptions are large in this case, the results undoubtedly show that the LED system provide significant savings in both electricity consumption and carbon emissions. As shown in Figure 10 and 11, the LED option produces 77% less carbon emissions and electricity consumption on an annual basis. While this was to be expected, the more important results were financial – without factoring in maintenance savings (not include because the lack of data), the simple payback period for the LED system would be 15.57 years. This shows that, while energy and emissions reductions are significant, costs still remain prohibitive; factoring in maintenance savings would likely decrease this payback period, though. As the technology improves, costs will decrease, meaning that Duke Athletics and FMD should continue to examine the possibility of LED stadium lighting into the future.

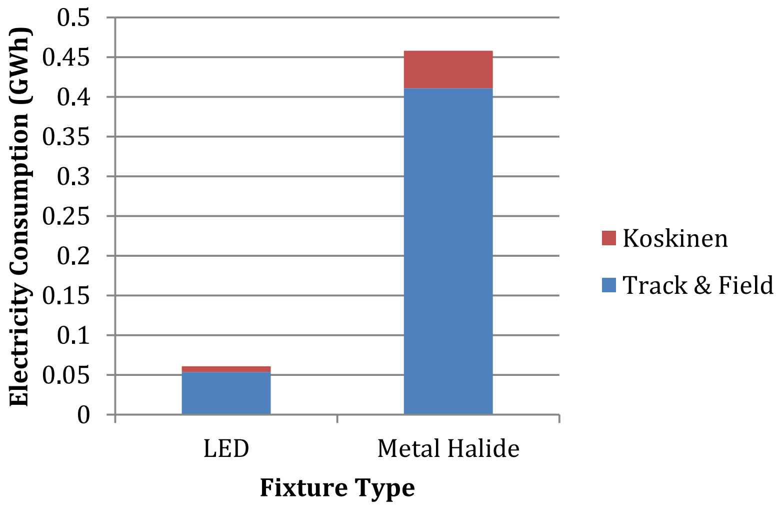

Figure 10, Estimated annual energy consumption for each lighting system

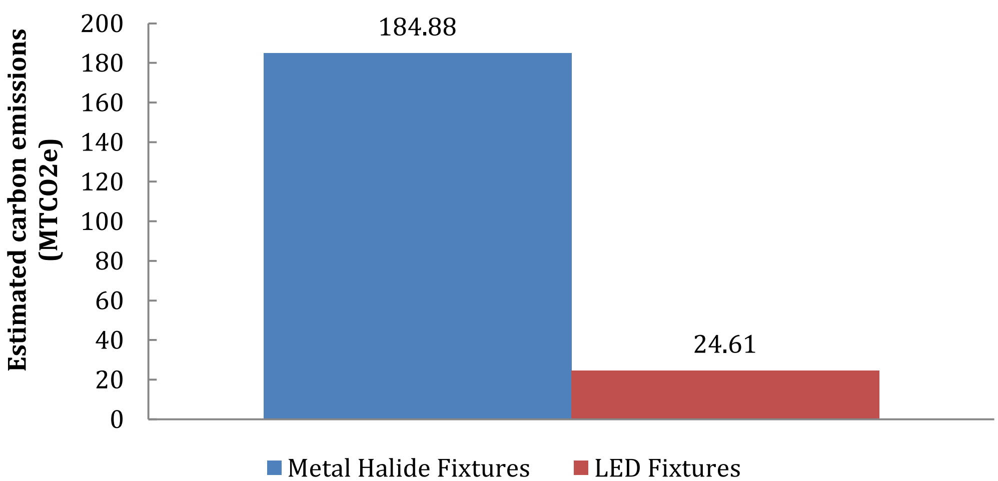

Figure 11, Estimated annual carbon dioxide emissions for each lighting system

XIII. Recommendations & Conclusions

The information laid out in regards to the ten materials and technologies in this study are meant to serve as the beginnings of a framework for both Duke FMD and Duke Athletics, in order to facilitate more environmentally sustainable decision making. In the process of doing so, a number of difficulties were encountered, most notably in the lack of information about what materials were to be used in Kennedy Tower. The bill of materials that was obtained from the general contractor provided only estimates of a small number of materials (which have been included in this study). As a result, I recommend that the university requires greater upstream disclosure from contractors regarding the materials they plan to use; this can be achieved through adding stipulations to contracts, along with holding training sessions for the contractor's employees.

Similarly, this study only represents the beginning of improving material and technology purchases at Duke. While Kennedy Tower was used as a case study, the goal is for the information provided here to be used in future construction projects and remodels. In addition to that, only a small number of materials and technologies have been covered, leaving an opportunity for future studies to expand on this framework. It is recommended that this comes through future partnerships between Duke FMD, Duke Athletics, and the Nicholas School of the Environment in the form of masters projects, like this one.

Lastly, the table on the next page has been created to provide a short summary of the recommendations made for each material and technology examined in the study.

Material/Technology	Recommendations
Cement	• Blend cement with additives such as fly ash or pozzolans. • Avoid excessive cement in concrete design. • Explore alternative binders such as lime and gypsum as a substitute for cement
Rebar	• Use the highest feasible amount of recycled steel content as possible. • Black rebar should be utilized if the project allows, avoiding the environmental impacts of epoxy coatings.
Sand & Stone	• Any materials sourced via marine routes should be avoided entirely. • If recycled aggregates are used, its quality needs to assessed due to potential performance issues.
Gypsum Board	• Purchase gypsum board that has been GREENGUARD Gold Certified to ensure low VOC emissions • Ask manufacturers for gypsum board with the highest recycled and synthetic gypsum content available • Make sure paper facing is from recycled sources
Insulation	• Because of the varied applications and insulations available, consult products with environmental product declarations to understand their impact • Also consider price, manufacturing location, possession of third-party certifications, and compliance with applicable codes and law.
Paint	• Follow SCAQMD’s Rule 1113 for VOC limits • Depending on application, explore processes such as UV and EB curing and zinc primer coatings • Test performance of multiple paints prior to selection; low VOC paints often have poor hiding power and require more paint.
Energy	• Factors are going against solar at Duke, but continue to study their viability in upcoming years • Micro wind turbines are a visible way to show a commitment to sustainability
Green Roofing	• Intensive green roofs have the most positive environmental impacts. • Provide an opportunity for student group to “own” a green roof
Lighting	• LED stadium light is likely still too expensive, but further studies now and in the future are needed.

Table 15, Summary of recommendations made in this study

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XV. Appendix

List of Tables & Figures

	Primary fragmentation	Loading & hauling	Primary crushing	Scalping screening	Secondary crushing	Tertiary crushing	Quaternary crushing	Final screening	Backfill	Total impact
Global Warming (kg CO2 eq.)	4.47E-02 - 1.11E-01	7.83E-02 - 1.94E-01	2.66E-01 - 9.52E-01	5.68E-03 - 1.63E-01	7.94E-02 - 7.50E-01	1.68E-02 - 5.31E-01	3.99E-01	1.38E-01 - 1.87E-01	1.05E-02	**1.48 - 2.52**
Eutrophication (kg PO4 eq.)	1.35E-04 - 1.38E-04	4.21E-05 - 9.31E-05	7.14E-05 - 2.55E-0E	2.77E-06 - 7.97E-05	2.13E-05 - 2.01E-04	4.98E-05 - 1.42E-04	1.07E-04	4.02E-05 - 7.25E-05	3.83E-07	**5.51E-04 - 8.78E-04**
Acidification (kg SO2 eq.)	5.45E-04 - 8.87E-04	4.90E-04 - 1.22E-03	1.47E-03 - 5.24E-03	4.93E-05 - 1.42E-03	4.37E-04 - 4.13E-03	1.02E-04 - 2.92E-03	2.20E-03	7.60E-04 - 1.06E-03	5.49E-06	**8.58E-03 - 1.48E-02**
Photo-oxidant formation (kg ethylene eq.)	2.70E-05 - 9.07E-05	6.71E-05 - 1.73E-04	8.40E-05 - 3.00E-04	4.41E-06 - 1.27E-05	2.50E-05 - 2.37E-04	5.87E-05 - 1.67E-04	1.26E-04	4.34E-05 - 7.57E-05	8.15E-05	**6.78E-04 - 9.94E-04**
Human toxicity (kg 1,4-DB eq.)	1.00E-01 - 1.72E-01	5.79E-02 - 6.18E-02	3.97E-02 - 8.59E-02	2.13E-02 - 2.17E-02	5.92E-03 - 5.59E-02	4.71E-03 - 7.46E-02	2.77E-02	1.30E-02 - 3.77E-02	1.15E-03	**3.37E-01 - 4.08E-01**
Freshwater Aquatic Ecotoxicity (kg 1,4-DB eq.)	1.97E-05 - 1.62E-03	1.47E-03 - 3.87E-03	3.99E-04 - 1.43E-03	6.76E-05 - 1.94E-03	1.19E-04 - 1.12E-03	2.78E-05 - 7.94E-04	5.98E-04	2.03E-04 - 8.07E-04	1.81E-05	**5.98E-03 - 9.00E-03**
Marine Aquatic Ecotoxicity (kg 1,4-DB eq.)	3.07E-01 - 25.27	22.97 - 60.27	13.01 - 46.42	1.20E-03 - 34.45	3.88 - 36.63	9.08E-01 - 25.90	1.95E+01	6.61 - 16.27	2.82E-01	**124.74 - 198.40**
Terrestrial Ecotoxicity (kg 1,4-DB eq.)	8.69E-06 - 7.16E-04	6.51E-04 - 1.71E-03	1.91E-04 - 6.82E-04	3.02E-05 - 8.67E-04	5.69E-05 - 5.37E-04	1.33E-05 - 3.80E-04	2.86E-04	9.69E-05 - 3.64E-04	7.89E-06	**2.71E-03 - 4.10E-03**
Ozone layer depletion (kg R11 eq.)	1.65E-11 - 1.36E-09	1.23E-09 - 3.23E-09	3.90E-08 - 1.39E-07	8.82E-10 - 2.54E-08	1.16E-08 - 1.10E-07	2.73E-09 - 7.77E-08	5.86E-08	1.98E-08 - 2.39E-08	1.51E-11	**1.85E-07 - 3.39E-07**

Table 16, Life cycle inventory results for 1 metric ton of crushed rock (Korre & Durucan, 2009)

	Overburden removal	Excavation	Loading and Conveying	Pre-processing storage	Scalping screening	Crushing	Sizing screening	Washing-scrubbing	Wet classification	De-watering	Product storage	Pit preparation	Re-vegetation	Total impact
Global Warming (kg CO2 eq.)	4.91E-03 - 0.36	7.66E-02	1.55E-01 - 9.19E-01	1.14E-01 - 1.96E-01	1.97E-02 - 1.68E-01	4.19E-01	1.97E-02 - 5.88E-01	2.22E-02 - 5.71E-01	1.97E-02 - 4.19E-01	4.92E-03 - 2.91E-01	2.09E-03 - 6.49E-01	1.53E-05 - 3.31E-04	3.99E-07 - 3.13E -04	**0.27 - 2.39**
Eutrophication (kg PO4 eq.)	7.75E-06 - 1.96E-04	3.58E-05	8.93E-05 - 2.54E-04	3.06E-05 - 8.67E-05	1.49E-05 - 4.49E-05	1.12E-04	1.49E-05 - 1.57E-04	1.67E-05 - 1.53E-04	1.49E-05 - 1.12E-04	3.72E-06 - 7.80E-05	3.27E-06 - 1.73E-04	2.17E-08 - 5.25E-07	6.35E-10	**1.66E-04 - 7.43E-04**
Acidification (kg SO2 eq.)	2.98E-05 - 2.25E-03	4.80E-04	9.67E-04 - 5.09E-03	6.29E-04 - 1.08E-03	5.72E-05 - 9.23E-04	2.31E-03	5.72E-05 - 3.23E-03	6.43E-05 - 3.14E-03	5.72E-05 - 2.31E-03	1.43E-05 - 1.60E-03	1.26E-05 - 3.57E-03	9.35E-08 - 2.02E-06	2.44E-09 - 1.91E-06	**1.34E-03 - 1.35E-02**
Photo-oxidant formation (kg ethylene eq.)	1.42E-06 - 3.07E-04	6.87E-05	1.29E-04 - 3.16E-04	3.60E-05 - 1.45E-04	3.82E-06 - 5.28E-05	1.32E-04	3.82E-06 - 3.49E-04	8.95E-07 - 7.69E-03	3.82E-06 - 3.47E-04	9.56E-07 - 9.19E-05	5.48E-07 - 2.04E-04	5.57E-09 - 9.01E-08	1.09E-10 - 8.52E-08	**1.61E-04 - 8.47E-03**
Human toxicity (kg 1,4-DB eq.)	1.71E-03 - 7.98E-01	8.61E-03	2.58E-02 - 6.67E-02	1.32E-02 - 2.01E-02	8.80E-03 - 6.08E-02	7.14E-02	4.93E-02 - 6.17E-02	1.56E-04 - 3.96E-02	1.41E-04 - 2.90E-02	3.51E-05 - 2.02E-02	4.26E-03 - 4.79E-02	4.40E-06 - 1.78E-04	3.77E-10 - 2.95E-07	**1.25E-01 - 3.49E-01**
Freshwater Aquatic Ecotoxicity (kg 1,4-DB eq.)	6.76E-13 - 3.37E-03	7.69E-04	1.40E-03 - 1.76E-03	1.71E-04 - 1.58E-03	4.32E-17 - 2.51E-04	6.27E-04	4.32E-17 - 8.80E-04	5.33E-04 - 8.55E-04	4.32E-17 - 6.27E-04	1.08E-017 - 5.34E-04	6.77E-13 - 9.70E-04	9.57E-14 - 2.27E-08	-	**1.58E-03 - 6.50E-03**
Marine Aquatic Ecotoxicity (kg 1,4-DB eq.)	1.67E-11 - 52.48	1.20E+01	21.85 - 49.78	5.58 - 24.68	-	-	-	-	-	-	-	-	-	**27.4 - 152.92**
Terrestrial Ecotoxicity (kg 1,4-DB eq.)	9.88E-14 - 1.49E-03	3.39E-04	6.19E-04 - 8.27E-04	8.18E-05 - 6.99E-04	4.08E-18 - 1.20E-04	3.00E-04	4.08E-18 - 4.21E-04	2.55E-04 - 4.09E-04	4.08E-18 - 6.78E-04	1.02E-18 - 2.40E-04	1.18E-13 - 4.64E-03	1.61E-14 - 1.00E-08	-	**6.99E-04 - 2.98E-03**
Ozone layer depletion (kg R11 eq.)	1.49E-09 - 5.63E-09	1.29E-09	2.35E-09 - 1.29E-07	2.65E-09 - 2.87E-08	9.49E-09 - 2.45E-08	6.14E-08	3.69E-08 - 8.92E-08	5.22E-08 - 2.26E-07	5.16E-08 - 6.14E-08	1.26E-08 - 4.27E-08	9.49E-08	3.80E-14	-	**2.65E-09 - 4.44E-07**

Table 17, Life cycle inventory results for 1 metric ton of land won sand and gravel (Korre & Durucan, 2009)

	Marine aggregates loading	**Marine aggregates discharge**	**Wharf processes**	**Total impact**
Global Warming (kg CO2 eq.)	32.79 - 40.30	0.255 - 0.357	1.06	**34.10 - 41.61**
Eutrophication (kg PO4 eq.)	9.28E-02 - 0.115	8.76E-05 - 1.30E-04	2.87E-04	**9.32E-02 - 0.115**
Acidification (kg SO2 eq.)	0.599 - 0.740	1.03E-03 - 1.61E-03	5.84E-03	**0.606 - 0.747**
Photo-oxidant formation (kg ethylene eq.)	4.749E-02 - 5.90E-02	1.44E-04 - 2.27E-04	3.49E-04	**4.83E-02 - 5.95E-02**
Human toxicity (kg 1,4-DB eq.)	8.72 - 10.78	1.56E-02 - 2.48E-02	9.01E-02	**8.83 - 10.89**
Freshwater Aquatic Ecotoxicity (kg 1,4-DB eq.)	4.08 - 5.06	1.56E-03 - 2.50E-03	1.81E-03	**4.09 - 5.06**
Marine Aquatic Ecotoxicity (kg 1,4-DB eq.)	236.83 - 241.24	24.30 - 38.89	5.45E+01	**315.60 - 334.60**
Terrestrial Ecotoxicity (kg 1,4-DB eq.)	2.18E-02 - 2.53E-02	6.88E-04 - 1.10E-03	8.54E-04	**2.34E-02 - 2.68E-02**
Ozone layer depletion (kg R11 eq.)	1.70E-08 - 1.91E-08	2.61E-09 - 4.17E-09	1.52E-07	**3.30E-09 - 1.75E-07**

Table 18, Life cycle inventory results for 1 metric ton of marine sand and gravel (Korre & Durucan, 2009)

	Waste reception	Crushing	Conveying & Magnetic separation	Washing	Secondary Crushing	Material Transport & Storage	Total Impact
Global Warming (kg CO2 eq.)	-	0.2304	7.72E-03	1.92	0.0659	0.1957	**2.42**
Eutrophication (kg PO4 eq.)	-	7.22E-05	1.60E-06	5.25E-04	1.37E-05	9.27E-05	**7.06E-04**
Acidification (kg SO2 eq.)	-	2.78E-04	6.16E-06	1.06E-02	5.26E-05	1.22E-03	**1.21E-02**
Photo-oxidant formation (kg ethylene eq.)	-	1.70E-05	4.12E-07	6.05E-04	3.52E-06	1.74E-04	**8.00E-04**
Human toxicity (kg 1,4-DB eq.)	1.08E-05	9.43E-02	4.39E-04	1.39E-01	2.14E-02	2.24E-02	**1.73E-01**
Freshwater Aquatic Ecotoxicity (kg 1,4-DB eq.)	-	6.19E-12	4.65E-18	2.86E-03	3.97E-17	1.96E-03	**1.96E-03**
Marine Aquatic Ecotoxicity (kg 1,4-DB eq.)	-	1.83E-10	2.59E-17	9.32E+01	2.21E-16	3.05E+01	**3.05E+01**
Terrestrial Ecotoxicity (kg 1,4-DB eq.)	-	1.04E-12	4.40E-19	1.37E-03	3.76E-18	8.62E-04	**8.62E-04**
Ozone layer depletion (kg R11 eq.)	-	-	-	2.80E-07	-	3.27E-09	**2.83E-07**

Table 19, Life cycle inventory results for 1 metric ton of recycled aggregate (Korre & Durucan, 2009)

Manufacturer	Product Name	Post-Consumer Recycled Content	Pre-Consumer Recycled Content	Recyclable?	Manufacturing Locations (if multiple, only closest to Durham, NC)
American Gypsum Company	M-Bloc® Type X with Mold & Moisture Resistance	5.0%	94.0%	Yes	Georgetown, SC
American Gypsum Company	FireBloc® Type C Gypsum Wallboard	5.0%	94.0%	Yes	Georgetown, SC
American Gypsum Company	FireBloc® Type X Gypsum Wallboard	5.0%	94.0%	Yes	Georgetown, SC
American Gypsum Company	M-Bloc Type C with Mold Resistance	5.0%	94.0%	Yes	Georgetown, SC
American Gypsum Company	M-Bloc® AR Type X Wallboard	5.0%	94.0%	Yes	Georgetown, SC
American Gypsum Company	M-Bloc® IR Type X Wallboard	5.0%	94.0%	Yes	Georgetown, SC
CertainTeed	Abuse Resistant Type X Gypsum Board	2.0%	98.0%	Yes	Moundsville, WV
CertainTeed	Evenwall Type X Gypsum Board	0.8%	2.5%	Yes	Fort Dodge, IA
CertainTeed	Type C Gypsum Board	0.3%	95.4%	Yes	Roxboro, NC
CertainTeed	Exterior Soffit Board Type X	3.1%	0.5%	Yes	Nashville, AR
CertainTeed	Type X Gypsum Board	0.3%	98.9%	Yes	Roxboro, NC
CertainTeed	Veneer Plaster Base, Type X Gypsum Board	2.0%	97.0%	Yes	Moundsville, WV
CertainTeed	ProRoc Extra Abuse Type X with M2Tech	unknown	unknown	unknown	unknown
Georgia-Pacific	ToughRock Fireguard C Gypsum Board	1.0%	4.0%	Yes	Savannah, GA
Lafarge	Fire Watercheck Type X	unknown	unknown	unknown	unknown
Lafarge	Firecheck Plasterbase Type X	5.0%	94.0%	No	Buchanan, NY
Lafarge	Firecheck Sheathing Type X	5.0%	94.0%	No	Palatka, NY
Lafarge	Firecheck Soffitboard Type X	5.0%	94.0%	No	Palatka, NY

Manufacturer	Product Name	Post-Consumer Recycled Content	Pre-Consumer Recycled Content	Recyclable?	Manufacturing Locations (if multiple, only closest to Durham, NC)
Lafarge	Firecheck Type C	5.0%	94.0%	No	Buchanan, NY
Lafarge	Firecheck Type X	5.0%	94.0%	No	Buchanan, NY
Lafarge	Mold Defense Type X	5.0%	94.0%	No	Buchanan, NY
Lafarge	Protecta HIR 300 Type X with Mold Defense	5.0%	94.0%	Yes	Georgetown, SC
Lafarge	Rapid Deco Level 5 Type X	5.0%	94.0%	No	Palatka, FL
Lafarge	Rapid Deco Level 5 Type X with Mold Defense	5.0%	94.0%	No	Palatka, FL
Lafarge	Weather Defense Platinum Interior Type X	0.0%	94.0%	No	Palatka, FL
National Gypsum	Gold Bond Brand Fire-Shield Gypsum Board	5.0%	95.0%	unknown	Mount Holly, NC
National Gypsum	Gold Bond Gridstone Fire-Shield Gypsum Ceiling Panels	unknown	unknown	unknown	unknown
National Gypsum	Gold Bond® BRAND High Strength Fire-Shield® LITE™ 30 Gypsum Board	5.0%	95.0%	unknown	Gibsonton, FL

Table 20, Product Overview of GREENGUARD Gold Certified Gypsum Products (American Gypsum EcoScorecard, n.d.; CertainTeed EcoScorecard, n.d.; LaFarge Gypsum EcoScorecard, n.d.; Green Product Score, n.d.; Georgia-Pacific Gypsum Sustainable Materials Data Sheet, 2012)

Impact category	Unit	Total	On-site process emissions/flows	Gypsum material (mined, quarried, and FGD gypsum; post-consumer gypsum)	Gypsum paper	Dry and wet additives	Lubricants, hyrdraulic fluid, and greases	On-site energy consump-tion	Inbound/ Outbound transportation	Packaging material	Off-spec GWBs used as bunks	Internal gypsum waste-close loop recycling	Waste disposal
Global warming	kg CO2 eq	315.429	0	-18.814	40.458	14.774	0.009	258.261	19.847	0.874	0.55	-0.651	0.121
Acidification	H+ moles eq	127.037	0	-5.968	15.846	5.333	0.004	100.894	10.668	0.386	0.252	-0.357	-0.02
Respiratory effects	kg PM2.5 eq	0.609	1.80E-02	0.04	0.072	0.025	0	0.443	0.01	0.002	0.001	-0.002	0
Eutrophication	kg N eq	3.70E-01	0	-1.60E-03	9.10E-02	9.10E-02	3.00E-05	1.70E-01	9.50E-03	3.20E-03	1.90E-03	-4.70E-04	5.40E-04
Ozone depletion	kg CFC-11 eq	1.50E-05	0	-2.00E-07	1.20E-06	1.10E-06	5.60E-09	1.30E-05	8.20E-10	7.70E+00	2.10E-08	-1.30E-09	1.20E-08
Smog	kg NOx eq	0.632	0	-0.15	0.083	0.046	0	0.447	0.207	0.003	0.002	-0.006	-0.001
Total Primary Energy	MJ	5445.1	0	-248.8	666.8	334.3	0.7	4382.8	269.5	45.7	10	-9.1	-6.9
Non renewable, fossil	MJ	5047.7	0	-253.3	612.7	203	0.7	4197.8	267.1	19.3	8.1	-8.9	1.2
Non-renewable, nuclear	MJ	242.9	0	3.7	45.8	20.7	1.20E-02	166.9	2.4	2.6	7.10E-01	-2.50E-01	4.10E-01
Non-renewable, biomass	MJ	2.6	0	-6.00E-06	2.10E-02	2.5	1.50E-07	0.00E+00	2.10E-09	1.10E-04	2.50E-02	-1.70E-08	1.50E-02
Renewable, biomass	MJ	124.3	0	-5.30E-04	3.1	105.4	1.60E-04	0.1	5.20E-05	2.30E+01	1.1	-1.90E-04	-8.60E+00
Renewable, wind solar, geothermal	MJ	2.9	0	1.00E-01	0.6	0.3	1.80E-04	1.9	1.10E-03	5.10E-02	9.00E-03	-3.10E-03	8.00E-03
Renewable, water	MJ	24.7	0	7.00E-01	4.6	2.5	1.30E-03	16.1	9.30E-03	6.00E-01	7.70E-02	-2.10E-02	3.70E-02
Abiotic depletion (excluding energy)	kg Sb eq	6.20E-03	0	6.00E-03	4.30E-07	2.90E-04	1.10E-10	4.60E-08	2.60E-11	2.10E-07	6.00E-05	-1.70E-04	-4.90E-08
Water use	m3	4.086	1	1.67E-01	0.847	0.461	1.90E-04	1.40E+00	8.10E-04	5.80E-02	2.60E-02	-5.00E-03	-6.90E-03

Table 21, Weighted Average 5/8" Type X GWB LCIA results - absolute basis, per MSF (Bushi & Meil, 2011)

Type	Insulation Materials	Where Applicable	Installation Methods	Advantages
Blanket: batts and rolls	•Fiberglass •Mineral (rock or slag) wool •Plastic fibers •Natural fibers	• Unfinished walls, including foundation walls • Floors and ceilings	Fitted between studs, joists, and beams.	• Suited for standard stud and joist spacing that is relatively free from obstructions. • Relatively inexpensive.
Concrete block insulation and insulating concrete blocks	Foam board, to be placed on outside of wall (usually new construction) or inside of wall (existing buildings): Some manufacturers incorporate foam beads or air into the concrete mix to increase R-values	• Unfinished walls, including foundation walls, for new construction or major renovations • Walls (insulating concrete blocks)	• Require specialized skills • Insulating concrete blocks are sometimes stacked without mortar (dry-stacked) and surface bonded.	• Insulating cores increases wall R-value. • Insulating outside of concrete block wall places mass inside conditioned space, which can moderate indoor temperatures. • Autoclaved aerated concrete and autoclaved cellular concrete masonry units have 10 times the insulating value of conventional concrete.
Foam board or rigid foam	• Polystyrene • Polyisocyanurate • Polyurethane	• Unfinished walls, including foundation walls • Floors and ceilings • Unvented low-slope roofs	Interior applications: must be covered with 1/2-inch gypsum board or other building-code approved material for fire safety. Exterior applications: must be covered with weatherproof facing.	• High insulating value for relatively little thickness. • Can block thermal short circuits when installed continuously over frames or joists.
Insulating concrete forms (ICFs)	• Foam boards or foam blocks	• Unfinished walls, including foundation walls for new construction	Installed as part of the building structure.	Insulation is literally built into the home's walls, creating high thermal resistance.
Loose-fill and blown-in	• Cellulose • Fiberglass • Mineral (rock or slag) wool	• Enclosed existing wall or open new wall cavities • Unfinished attic floors • Other hard-to-reach places	Blown into place using special equipment, sometimes poured in.	Good for adding insulation to existing finished areas, irregularly shaped areas, and around obstructions.
Reflective system	• Foil-faced kraft paper, plastic film, polyethylene bubbles, or cardboard	• Unfinished walls, ceilings, and floors	Foils, films, or papers fitted between wood-frame studs, joists, rafters, and beams.	• Suitable for framing at standard spacing. • Bubble-form suitable if framing is irregular or if obstructions are present. • Most effective at preventing downward heat flow, effectiveness depends on spacing.
Rigid fibrous or fiber insulation	• Fiberglass • Mineral (rock or slag) wool	• Ducts in unconditioned spaces • Other places requiring insulation that can withstand high temperatures	HVAC contractors fabricate the insulation into ducts either at their shops or at the job sites.	Can withstand high temperatures.
Sprayed foam and foamed-in-place	• Cementitious • Phenolic • Polyisocyanurate • Polyurethane	• Enclosed existing wall • Open new wall cavities • Unfinished attic floors	Applied using small spray containers or in larger quantities as a pressure sprayed (foamed-in-place) product.	Good for adding insulation to existing finished areas, irregularly shaped areas, and around obstructions.
Structural insulated panels (SIPs)	• Foam board or liquid foam insulation core • Straw core insulation	• Unfinished walls, ceilings, floors, and roofs for new construction	Construction workers fit SIPs together to form walls and roof of a structure.	SIP-built structures provide superior and uniform insulation compared to more traditional construction methods; they also take less time to build.

Table 22, Overview of common insulating materials (Insulation, n.d.)

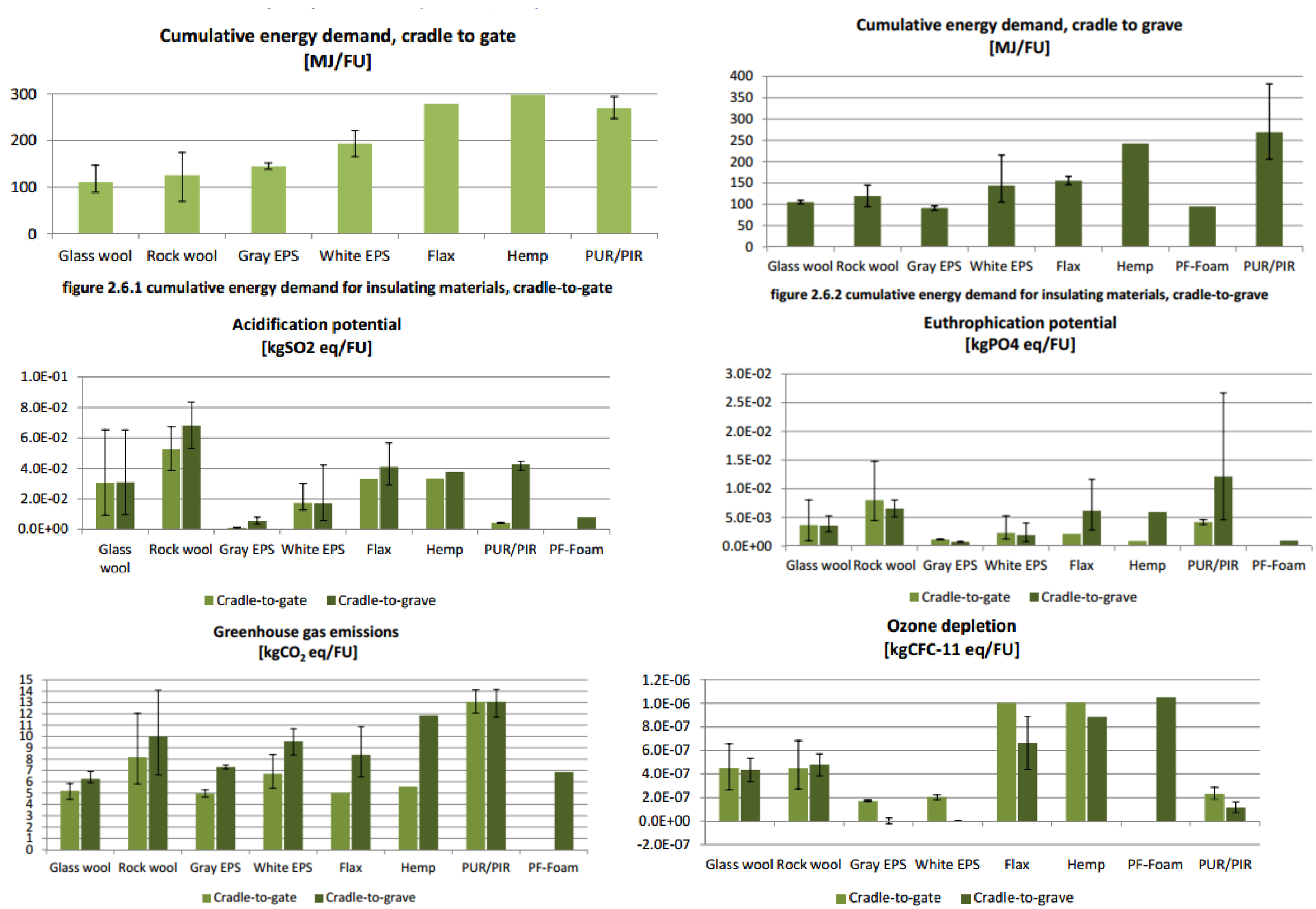

Figure 12, Life cycle inventory of selected insulating materials (Duijve, 2012)

Manufacturer	Product Type	Product Name	Manufacturing Location	Pre-Consumer Recycled Content	Post-Consumer Recycled Content	Total Recycled Content	Certification
CertainTeed	Blowing Wool Fiberglass Insulation	InsulSafe® SP, TrueComfort®, UltraComfort®, OPTIMA®, InsulSafe®	Athens, GA	29%	8%	37%	GREENGUARD Gold
CertainTeed	Sustainable Insulation	Unfaced & Kraft Faced Batts	Athens, GA	28% (unfaced), 23% (kraft faced)	7% (unfaced), 6% (kraft faced)	35% (unfaced), 29% (kraft faced)	GREENGUARD Gold; kraft facing is certified by the Sustainable Forestry Initiative (SFI)
Dow Corning	Vacuum Insulation Panels	Vacuum Insulation Panels	unknown	unknown	unknown	unknown	
Kingspan	Insulated Wall & Roof Panel Systems	Insulated Wall & Roof Panel Systems	Columbus, OH (2-inch laminated panels); Deland, FL (3-inch CPL panels)	unknown	unknown	unknown	
Knauf	Unfaced and Kraft Faced Batts and Rolls	EcoBatt® Insulation with ECOSE® Technology Batts	Shelbyville, IN	0%	59%	59%	GREENGUARD Gold
Knauf	Unbonded, fibrous glass blowing insulation	Jet Stream® ULTRA	Shelbyville, IN	0%	62%	62%	GREENGUARD Gold
Owens Corning	XPS	EcoTouch Unfaced Insulation	Fairburn, GA	1-32%	41-64%	Minimum 65-73%	GREENGUARD
Owens Corning	XPS	FOAMULAR® XPS Insulation	Tallmadge, OH	20%	0%	20%	GREENGUARD Gold
Owens Corning	XPS	Kraft Faced Insulation	Fairburn, GA	22%	36%	Minimum 58%	GREENGUARD
Owens Corning	XPS	Unbonded Loosefill Insulation	Mt. Vernon, OH	24%	41%	Minimum 65%	GREENGUARD

Table 23, Overview of insulating materials with EPDs (Sustainable Product Guide, n.d.)

Manufacturer	Product Type	Product Name	Global Warming (kg CO_2 eq)	Acidification (kg SO_2 eq or mol H+ eq)	Eutrophication (kg PO_4 eq or kg N eq)	Smog (kg O_3 eq or kg C2H4 eq)	Ozone Depletion (kg CFC-11 eq)	Waste to Landfill (kg)	Metered Water (kg)	Energy (MJ-eq)
CertainTeed	Blowing Wool Fiberglass Insulation	InsulSafe® SP, TrueComfort®, UltraComfort®, OPTIMA®, InsulSafe®	1.1E+00	4.3E-01 (mol H+ eq)	4.2E-04 (kg N eq)	5.8-E02 (kg O_3 eq)	1.7E-08	5.2E-01	4.1E+00	1.6E+01
CertainTeed	Sustainable Insulation	Unfaced & Kraft Faced Batts	1.2E+00 (unfaced); 1.2E+00 (kraft faced)	3.6E-01 (unfaced); 4.0E-01 (kraft faced) (mol H+ eq)	3.2E-04 (unfaced); 4.6E-04 (kraft faced) [kg N eq]	5.1E-02 (unfaced); 5.7E-02 (kraft faced) [kg O_3 eq]	1.4E-08 (unfaced); 3.3E-08 (kraft faced)	4.1E-01(unfaced); 4.6E-01 (kraft faced)	3.5E+00 (unfaced); 4.6E+00 (kraft faced)	1.5E+01 (unfaced); 1.8E+01 (kraft faced)
Dow Corning	Vacuum Insulation Panels	Vacuum Insulation Panels	41.59	1.95E-01 (kg SO_2 eq)	2.09E-02 (kg N eq)	2.079(kg O_3 eq)	1.07E-04	4.67E-01	4.21E-02	687.25
Kingspan	Insulated Wall & Roof Panel Systems	Insulated Wall & Roof Panel Systems	9.25E+02 (laminated); 1.17E+03 (CPL)	1.69E+02 (laminated); 2.51E+02 (CPL) [kg SO_2 eq]	1.70E-01 (laminated); 1.83E-01 (CPL)	1.75E-03 laminated); 2.30E-03 (CPL) (kg C_2H_4 eq)	3.05E-05 (laminated); 4.23E-05 (CPL)	5.33E+00 (laminated); 6.11E+01 (CPL)	3.75E+00 (laminated); 6.01E+00 (CPL)	1.66E+04 (laminated); 1.50E+04 (CPL)
Knauf	Unfaced and Kraft Faced Batts and Rolls	EcoBatt® Insulation with ECOSE® Technology Batts	6.65E-01 (unfaced); 8.49E-01 (kraft faced)	1.66E-01 (unfaced); 1.97E-01 (kraft faced) (mol H+ eq)	2.16E-04 (unfaced); 3.40E-04 (kraft faced) (kg N eq)	2.50E-02 (unfaced); 3.29E-02 (kraft faced) [kg O_3 eq]	1.37E-10 (unfaced); 2.14E-10 (kraft faced)	3.59E-01 (unfaced); 4.54E-01 (kraft faced)	1.23E+00 (unfaced & kraft faced)	1.16E+01 (unfaced); 1.65E+01 (kraft faced)
Knauf	Unbonded, fibrous glass blowing insulation	Jet Stream® ULTRA	7.89E-01	1.11E-01 (mol H+ eq)	1.10E-04 (kg N eq)	2.69E-02 (kg O_3 eq)	1.72E-10	3.86E-01	9.95E-01	1.26E+01
Owens Corning	XPS	EcoTouch Unfaced Insulation	6.18E-01	2.37E-01 (mol H+ eq)	3.82E-04 (kg N eq)	3.81E-02 (kg O_3 eq)	1.70E-08	3.98E-01	4.76E+00	9.92E+00
Owens Corning	XPS	FOAMULAR® XPS Insulation	6.08E+01	1.78E+00 (mol H+ eq)	9.85E-04 (kg N eq)	2.08E-01 (kg O_3 eq)	3.63E-04	8.57E-01	3.79E+01	8.07E+01
Owens Corning	XPS	Kraft Faced Insulation	7.53E-01	2.99E-01 (mol H+ eq)	5.40E-04 (kg N eq)	5.44E-02 (kg O_3 eq)	2.42E-08	5.15E-01	1.52E+01	1.67E+01
Owens Corning	XPS	Unbonded Loosefill Insulation	1.07E+00	4.06E-01 (mol H+ eq)	2.69E-04 (kg N eq)	6.38E-02 (kg O_3 eq)	3.89E-08	6.35E-01	6.41E+00	1.66E+01

Table 24, LCIA results for insulating materials with EPDs (Sustainable Product Guide, n.d.)

The functional unit of these studies are 1 square meter of R_{si}=1, from cradle to grave. R_{si}=1 is equivalent to an American r-value of R-5.68. Table 25 (next page) gives scaling factors to multiply each impact category value, based on r-value.

Product (United Stated) Customary R-Value	Factor to Multiply Impact per m^2 of R_{si}=1 (dimensionless)
R-11	2.07
R-13	3.07
R-15	4.72
R-19	3.43
R-21	4.96
R-30	5.78
R-38	7.03

Table 25, R-Value Scaling Factors (Sustainable Product Guide, n.d.)

	PRODUCT			CONSTRUCTION PROCESS			USE				END OF LIFE			TOTAL EFFECTS			
Summary Measures	Manufacturing	Transport	**Total**	Construction-installation Process	Transport	**Total**	Replacement Manufacturing	Replacement Transport	Operational Energy Use Annual	**Total**	De-construction Demolition	Transport	**Total**	Non-Transport	Transport	Operational Energy Use	**Total**
Fossil Fuel Consumption (MJ)	116182.2516	0	**116182**	619.0970013	5749.4562	**6368.553**	0	0	0	**0**	76064.37677	330.3506	**76395**	192865.725	6079.807	0	**198945.5**
Global Warming Potential (kg CO2 eq)	10810.5	0	**10810.5**	2.840073659	442.27527	**445.1153**	0	0	0	**0**	8053.045359	25.15436	**8078.2**	18866.3854	467.4296	0	**19333.82**
Acidification Potential (kg SO2 eq)	48.63787694	0	**48.6379**	1.069034671	2.0434616	**3.112496**	0	0	0	**0**	21.12483507	0.117366	**21.242**	70.8317467	2.160827	0	**72.99257**
HH Particulate (kg PM2.5 eq)	55.75981696	0	**55.7598**	0.41270052	0.063356	**0.476057**	0	0	0	**0**	8.878420883	0.003625	**8.882**	65.0509384	0.066981	0	**65.11792**
Eutrophication Potential (kg N eq)	1.237290089	0	**1.23729**	0.056227804	0.1475014	**0.203729**	0	0	0	**0**	1.008301651	0.008462	**1.0168**	2.30181954	0.155963	0	**2.457782**
Ozone Depletion Potential (kg CFC-11 eq)	0	0	**0**	3.22019E-09	1.763E-08	**2.08E-08**	0	0	0	**0**	8.63559E-09	1E-09	**1E-08**	1.1856E-08	1.86E-08	0	**3.05E-08**
Smog Potential (kg O3 eq)	490.0210251	0	**490.021**	35.42098265	72.256907	**107.6779**	0	0	0	**0**	235.3465874	4.150025	**239.5**	760.788595	76.40693	0	**837.1955**

Table 26, LCIA results for rebar (Athena Impact Estimator for Buildings)

Paint Type	For:	Against
EB/UV Cured - Example Powder coats, Polyurethanes	• Low to zero solvent, reduced worker health impacts • Up to 90% energy savings against thermal curing systems • Factory applied, highly efficient low waste technology • Release virtually no hazardous air particles • Reduced paint volume, raw resource use	• Limited product availability
Acrylic	• Greatly reduced VOC emissions compared to Alkyd paints • Reduced impacts from clean-up - water based not mineral turps based	• Potential ongoing low-level emissions of range of products including formaldehyde and benzene • Use of fungicides and biocides to protect latex • In some applications may not give durability and wash & wear performance of alkyd paints • Very small ongoing emissions of acrylic monomer. Problematic for people with high chemical sensitivity.
Acrylic - Low VOC	• VOCs reduced by a further 20-40% • Reduced impacts from clean-up - water based not mineral turps based	• Still some potential from ongoing low-level emissions of range of products including formaldehyde and benzene • Use of fungicides and biocides to protect latex • In some applications may not give durability and wash & wear performance of alkyd paints • Very small ongoing emissions of acrylic monomer. Problematical for people with high chemical sensitivity.
Acrylic - Zero VOC	• Low VOCs across all tint ranges • Reduced impacts from clean-up - water based not mineral turps based • Some manufacturers have developed gloss/durability characteristics approaching alkyd	• Potential ongoing low-level emissions of range of products including formaldehyde • Use of fungicides and biocides to protect latex • Some acrylic enamels may not give durability and wash & wear performance of alkyd paints • Very small ongoing emissions of acrylic monomer. May be problematic for people with high chemical sensitivity.
Alkyd - Oil-based paints	• Does not use the full range of biocides and fungicides used by acrylic paints • In some applications may be more durable than acrylics • High gloss and smooth finishes	• High toxicity, high VOC emissions with known acute and carcinogenic health effects, though 'high alkyd' paints can reduce this somewhat • Significant clean up impacts from need for mineral-based solvents • High embodied energy
Polyurethane	• Durability	• High toxic, VOC emissions with known health effects • Significant clean up impacts from need for organic solvents • High embodied energy • Cyanide emissions during application and smoke generation
Polyurethane - Modified VOC and Iso Cyanate content	• Durability	• Reduced toxic VOC emissions with known health effects, • Significant clean up impacts from need for mineral-based solvents

		• High embodied energy • Reduced cyanide and VOC emissions during application and smoke generation
Epoxide	• Durability	• Highly allergenic constituents • Toxic VOCs • High embodied energy • Generate high levels of hazardous liquids and solids during base metal preparation
Epoxide - Low VOC	• Low VOC • Durability	• High embodied energy
Powder coats - Zero VOC	• Zero VOC • Low material wastage due to material recovery during application	• Difficult to patch without high VOC spray cans • High embodied energy
Natural Paints	• Can be based on greatly reduced VOC-impact natural turpenes • May be hydrocarbon free, reduced LCA impacts, GHG • Low Embodied Energy • May be based on biodegradable non-toxic ingredients • May be locally produced • Breathing surface • Abundant raw materials	• Durability and maintainability in some paints not as good as alkyd or acrylics • Caseine-based paints susceptible to fungal attack • Application of some paints can be labor and skill intensive
Lime Washes & Cement Paints	• Can be very low/ VOC free • Durable and suitable for exterior applications • High coverage • Breathing surface • Low embodied energy • Abundant raw materials	• Not easily scrubbed in interior uses • Rough to touch
Silicate Paints	• Zero VOC free • Durable and suitable for exterior applications • High coverage • Penetrates mineral substrates and forms micro crystalline bond with surface • Breathing surface • Low embodied energy • Abundant raw materials	• Only bonds to clean mineral surfaces • Not easily scrubbed in interior uses • Rough to touch

Table 27, Overview of Paint Types (Eco Priority Guide, n.d.)

	A	B	C	D	E	F	G	H	I	J	K	L
1		Existing System Tr&F	Existing System Koskinen			Proposed LED Tr&F				Proposed LED Koskinen		
2		Event Lights	Event Lights		Event Lights - Game Mode	Event Lights - Practice Mode 50%	General Use - 25% Light Levels		Event Lights - Game Mode	Event Lights - Practice Mode 50%	General Use - 25% Light Levels	
3												
4												
5	kWh Energy Consumption	182.97	19.26		63.3	31.65	15.825		6.963	3.4815	1.74075	
6												
7	Annual Hours of Estimated Usage Per Mode	2244	2460		72	918	1254	**Total**	360	774	1326	**Total**
8		410584.68	47379.6		4557.6	29054.7	19844.55	53456.85	2506.68	2694.681	2308.2345	7509.596
9	Total Annual Energy Cost Per Usage Mode	$30,342.21	$3,501.35		$336.81	$2,147.14	$1,466.51		$185.24	$199.14	$170.58	
10	**Total Annual Energy Costs - All Modes**	$33,843.56			$3,950.46				$554.96			
11												
12	Metal Halide Fixtures	$33,843.56	457,964.28	184.88				LED	Metal Halide			
13	LED Fixtures	$4,505.42	60,966.45	24.61			Track & Field	53456.85	410584.68			
14	**Estimated Savings**	$29,338.14	396,997.83	160.27			Koskinen	7509.596	47379.6			
15							Total	60966.45	457964.28			
16	**Energy Savings Return on Investment - Based on Current Electrical Rate**											
17	Estimated 10 Year Energy Savings	$293,381.40			Materials	Labor			Track & Field	Koskinen	Total	
18	Musco Estimated LED Turnkey Replacement Cost	$456,718.75			$341,093.75	$115,625.00		LED	0.05345685	0.007509596	60966.4455	
19	10 Year Cost of Ownership	$163,337.35						Metal Hali	0.41058468	0.0473796	457964.28	
20	Return on Investment Timeframe in Years	15.57										
21					Current System Assumptions							
22	**Carbon Savings**				Event Lighting (189) - 1000 Watt Metal Halide Fixtures - 1.07 kW Per Fixture = 202.23 kWh							
23	2012 Duke Energy Carbon intensity, lbs CO_2/kWh	0.89			Track & Field Complex (171) x 1.07 kW Per Fixture = 182.97 kWh							
24	Estimated annual energy reduction, kWh	396,997.83			Koskinen Stadium (18) x 1.07 kW Per Fixture = 19.26 kWh							
25	Estimated carbon emission reduction, lbs CO2e	353,328.07										
26	lbs/MT	2204.62			Proposed Musco LED System Information							
27	estimated carbon reduction, MTCO2e	160.27			Event Lighting (111) - Musco LED Fixtures - 0.633 kW Per Fixture = 70.263 kWh							
28					Track & Field Complex (100) x 0.633 kW Per Fixture = 63.3 kWh							
29					Koskinen Stadium (11) x 0.633 kW Per Fixture = 6.963 kWh							

Figure 13, Screenshot of the workbook used for the LED lighting analysis